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TITANIUM SHEET ROLLING PROGRAM

FOR

Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr

TWELFTH BIMONTHLY REPORT

Covers period 1 May - 30 June 1961

Prepared Under Navy, Bureau Of Naval Weapons' Contract NOas-59-6227-c

14 September 1961

Titanium Metals Corporation of America

TECHNICAL LABORATORY

TORONTO, OHIO

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Prepared by:

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14 September 1961

TITANIUM METALS CORPORATION OF AMERICA
TECHNICAL DEPARTMENT
Toronto, Ohio

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ABSTRACT

In this report period, twelve Ti-8Al-1Mo-1V sheets were duplex annealed at 1850F (5 min) AC + 1100F (8 hrs) and tested; although more process development is indicated, the results were nearly the same as achieved in laboratory treated samples. The study of the effect of ~~hydrogen~~ H on 1000F creep-stability and room-temperature notch properties of Ti-8Al-1Mo-1V ~~was completed which~~ showed that 150 ppm ~~hydrogen~~ H content is a safe level in both mill annealed and duplex annealed material. Uniform properties were found to exist through a representative sheet of Ti-8Al-1Mo-1V and a stress relieving investigation showed that temperatures of 1100-1300F are required to relieve residual stresses in short practical times. In the production phase of the contract, half of the 92 sheets of Ti-8Al-1Mo-1V has been tested and inspected, automatic release property specifications were established, and material was shipped to two Navy-approved customers. Processing of the balance of the 92 sheets and the last 1700-pound ingot to 1450F mill annealed sheet is continuing with an estimated completion date of August 31, 1961.

~~Several~~ Laboratory studies ~~were completed~~ on Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheets ~~which~~ showed that 0.010-0.012in should be removed from gage after finish rolling to remove processing contamination, particularly in Ti-7Al-12Zr; that 150 ppm ~~hydrogen~~ H is a safe level for Ti-5Al-5Sn-5Zr and 100 ppm appears to be tolerable in Ti-7Al-12Zr; and that slow cooling after final annealing adversely affects the creep resistance and ductility, especially the latter in Ti-7Al-12Zr. These investigations also showed that uniform properties are achieved throughout representative sheets of both alloys, that Ti-7Al-12Zr exhibits better creep-stability at 800 and 1100F than at 900-1000F, that temperatures of 1100-1300F are required to stress relieve both alloys in short practical times, and that Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr are much more susceptible to stress corrosion than Ti-8Al-1Mo-1V during a 1100F stress relief cycle. In the production phase of the contract, several sheets of both alloys have been completed and tested, thus permitting the acceptance of an automatic release property specification for Ti-5Al-5Sn-5Zr and the establishment of a temporary specification for Ti-7Al-12Zr, pending more property data. Processing of the balance of material from the four 1700-pound ingots of each alloy is continuing with an estimated completion date for all sheets of August 31, 1961.

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TWELFTH BIMONTHLY REPORT

TITANIUM SHEET ROLLING PROGRAM FOR

Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, AND Ti-7Al-12Zr

INTRODUCTION

The purpose of Contract NOas 59-6227-c is to establish optimum sheet processing procedures for three advanced alpha or essentially all-alpha titanium alloys; Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr; and to produce substantial quantities of sheet from each of the three for evaluation by Department of Defense contractors.

During previous report periods, one 3500-pound ingot of Ti-8Al-1Mo-1V was processed to sheet and optimum finish rolling and mill annealing temperatures were established. For the production phase of the contract, five 1600-pound ingots of Ti-8Al-1Mo-1V were processed to sheets with half of these being completed and tested. Mill operations were initiated on a sixth heat of Ti-8Al-1Mo-1V. Initial sheets of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr were rolled from two 1700-pound ingots and thoroughly evaluated to establish optimum finish rolling and annealing temperatures and to permit sheet processing the balance of the first two heats. In the production phase of the contract, processing of three 1700-pound ingots of each of the two alloys was initiated and several sheets were finish rolled.

In this, the twelfth report period covering May 1 - June 30, 1961, half of the 92 sheets from the five ingots of Ti-8Al-1Mo-1V was inspected and material was shipped to two Navy-approved customers; the other half of these sheets is being finished and tested. Sheets from a sixth ingot were rolled and finishing operations are continuing. Automatic release property specifications were established for Ti-8Al-1Mo-1V sheet. Twelve sheets from the initial ingot of Ti-8Al-1Mo-1V were duplex annealed and tested. Additional laboratory investigations were undertaken or completed on Ti-8Al-1Mo-1V to study the uniformity of properties of a typical sheet, to determine the effect of hydrogen on creep-stability, and to study the stress relief characteristics of welded sheet.

Rather comprehensive laboratory evaluation was completed or is in progress on Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr including a more thorough study of properties, processing contamination, investigation of the effects of hydrogen and annealing time and cooling rate on creep properties, and stress relief studies on welded sheet. Sheets from the first two ingots were tested and inspected and automatic release property specifications were proposed for each alloy. The balance of sheets from the first three 1700-pound ingots of each composition was finish rolled and processing continued with the completion and testing of several sheets. Mill operations were also initiated on the last 1700-pound heat of each of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr.

EVALUATION OF Ti-8Al-1Mo-1V SHEET

Several additional studies were continued or completed on Ti-8Al-1Mo-1V sheet to evaluate its properties and characteristics more thoroughly. Included were the duplex annealing and testing of 12 sheets, an investigation of the effect of hydrogen on the creep-stability and notch-rupture properties, property uniformity measurements in a typical sheet of Ti-8Al-1Mo-1V, and stress relief studies of welded sheet. Results of these investigations are described in the sections to follow.

Properties of Mill Duplex Annealed Sheets

Although a rather thorough evaluation of duplex annealed properties has previously been conducted on laboratory treated specimens (1, 2, 3), no full-size sheets had been annealed in this fashion utilizing mill procedures. Therefore, twelve sheets, which had previously been finished after mill annealing at 1350F (8 hrs), were selected from the first ingot (M-9519) and duplex annealed at 1850F (5 min) AC + 1100F (8 hrs). One 0.080in sheet from V-1555 was also treated with this group. As described in the Eleventh Bimonthly Report(3), no advantage was seen for using a protective coating to minimize contamination, so these sheets were solution annealed at 1850F (5 min) in an air-atmosphere, electrically-heated furnace, air cooled, descaled, and acid pickled. They were then transferred to a creep-flattening furnace, since some transverse ripples were present after the 1850F solution annealing operation, and stabilized at 1100F for 8 hours. Finish grinding, acid pickling, and testing followed with properties listed in Table 1.

As shown, the duplex annealed strengths of the 0.020in sheets were higher and elongations were lower than corresponding

TABLE 1. ROOM-TEMPERATURE TENSILE AND BEND PROPERTIES OF MILL DUPLEX ANNEALED Ti-8Al-1Mo-1V SHEETS (1850F (5 min) AC + 1100F (8 hrs) FC)

Heat No.	Gage, in	Test No.	Sheet No.	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	Bend Radius T	H_2 ppm
M-9519	0.020	A-7130	1	L	169.8	153.7	5.0(1)	4.2	250
				T	168.8	150.7	11.0	4.0	260
(Originally listed as 1350F mill annealed sheets under A-3805*)			2	L	171.5	154.7	6.0	5.0	230
				T	164.5	149.1	10.5	4.0	-
			3	L	174.0	162.5	4.5 (1)	4.2	230
				T	166.7	148.0	11.5 (1)	4.0	-
			4	L	175.3	162.8	5.0 (1)	4.2	270
				T	162.3	146.2	10.0	4.0	-
		Average		L	172.7	158.4	5.1 (1)	4.4	246
				T	165.6	148.5	10.8	4.0	-
M-9519	0.062	A-7067	1	L	156.6	141.3	14.5	4.1	70
				T	152.6	135.4	13.0	5.1	-
(Originally listed as 1350F mill annealed sheets under A-4087*)			2	L	149.8	133.5	13.0	4.1	80
				T	149.9	133.7	14.0	5.1	-
			3	L	154.1	135.1	14.0	4.7	80
				T	154.7	142.4	14.0	4.1	-
			4	L	154.1	142.8	14.0	5.1	70
				T	152.1	135.3	15.0	5.4	-
		Average		L	153.7	138.2	13.9	4.5	75
				T	152.3	136.7	14.0	4.9	-
V-1555M	0.080	A-7132	1	L	161.8	145.7	13.5	3.5	90
(Originally as A-5473, mill annealed at 1450F**)				T	156.9	144.2	14.0	3.5	-

(Continued)

TABLE 1. (Continued)

Heat No.	Gage, in	Test No.	Sheet No.	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	Bend Radius T	H_2 ppm
M9519	0.090	A-7066	1	L	146.1	131.3	17.0	3.5	90
				T	148.5	134.2	16.0	4.4	-
(Originally listed as 1350F mill annealed sheets under A-3715*)			2	L	148.7	134.8	13.0 (1)	3.5	90
				T	148.9	137.8	16.5	3.5	-
			3	L	150.8	137.4	15.0	3.5	120
				T	151.4	136.0	14.5	4.4	-
			4	L	151.4	134.8	14.5	4.4	130
				T	151.1	135.7	15.0	3.5	-
		Average		L	149.3	134.6	14.9	3.7	108
				T	150.0	135.9	15.5	4.0	-

* Properties listed in Table 1 of Fourth Bimonthly Report (4).
** Properties listed in Table 1 of Ninth Bimonthly Report (2).
(1) Broke at end of gage length.

values on the thicker sheets. However, this would be expected since, just as with laboratory treated samples, the cooling rate of thin gage material is much more rapid and, therefore, represents more of a solution than an annealing treatment. Hydrogen pick-up was also a problem in the 0.020in sheets, but not nearly as serious in the 0.062 and 0.090in material. Comparing the properties from mill duplex annealed Ti-8Al-1Mo-1V sheets in Table 1 with corresponding results from laboratory treated specimens(3), it is seen that the latter produced somewhat higher strengths and better bendability, particularly in the thinner gages. The higher strengths follow the pattern described above regarding cooling rates, while the lower bend radii are probably the result of more thorough surface cleaning obtained on laboratory samples.

It should be noted that 0.020in was the actual sheet gage prior to duplex annealing; consequently, grinding and pickling such thin material presented formidable problems and, no doubt, are associated in part with the high hydrogen and inferior bendability exhibited by these thin sheets. However, the problem of hydrogen pick-up in light-gage material cannot be ignored, since the 1850F solution annealing temperature is quite high. In an annealing process of this type, use of a protective coating may be necessary to minimize hydrogen contamination. To develop improved duplex annealing procedures, additional experience would be required particularly with thin sheets in an effort to obtain lower hydrogen contents and better ductility.

Based on the properties presented in Table 1 and those listed previously(3), the following property specification appears reasonable for duplex annealed Ti-8Al-1Mo-1V sheet:

UTS Ksi	YS(0.2%) Ksi	Elong (2in),%	Min Bend Radius,T	H_2 ppm
140	130	10	5.5	150

However, at the request of the Navy Bureau of Weapons, no Ti-8Al-1Mo-1V sheet will be duplex annealed for the present, since there appears to be no demand currently by Navy customers for material in this condition. As a result of this request, the proposed specification above will be held in abeyance and plans will be made to finish all sheets for the production phase of the contract in the 1450F (8 hrs) mill annealed condition.

Effect of Hydrogen on Creep-Stability and Notch Properties of Ti-8Al-1Mo-1V Sheet

As outlined in prior reports(2,3), a laboratory study was conducted to determine the effect of hydrogen on the 1000F creep-stability and room-temperature notch tensile and notch-rupture properties of Ti-8Al-1Mo-1V sheet. This was performed on a 0.062in sheet from the first heat, M-9519, which had originally been finish rolled from 1800F and mill annealed at 1350F (8 hrs).

As originally planned, the tests were to be made covering a range of hydrogen contents from 40 to 300 ppm in three conditions of heat treatment: simulated mill annealed at 1450F, duplex annealed at 1800/1850F (5 min) AC + 1100F (8 hrs), and beta duplex annealed at 1950F (5 min) AC + 1100F (8 hrs). Hydrogenation and annealing were combined in such a way that specimen blanks were outgassed in vacuum at 1350F, hydrogenated in a modified Sievert's apparatus at 1350F, and then given the 1450F simulated mill annealing cycle by sealing the samples inside of welded cover sheets of commercially pure titanium to prevent oxidation. Unfortunately, specimens of different hydrogen contents were sealed together in the same air-tight cover sheets and during the long-time annealing period, hydrogen contents equalized such that all specimens were at approximately the same hydrogen level. However, this situation was not discovered until the scheduled samples were subsequently duplex annealed and all had been tested. At this point, several samples were repeated, but because of inferior specimen preparation techniques, results of the repeat creep-stability tests are not considered valid. It should be noted that the 1450F (4 hrs) cycle with slow heating and cooling used in the laboratory approximates the 1450F (8 hrs) annealing cycle utilized in production facilities on a medium-size load of sheets.

Results of the investigation are listed in Table 2, showing that for the most part hydrogen contents fell in the range of 110 to 150 ppm. Limited data were obtained at 200-300 ppm, but are not considered valid because of sub-standard specimen preparation. Discounting the latter results, it is seen that no serious instability was encountered in 1450F mill annealed or 1800F (5 min) AC + 1100F (8 hrs) duplex annealed samples at hydrogen levels up to about 135 ppm, the highest contents for which reliable tests were obtained. Good room-temperature notch tensile and notch-rupture (5 hr sustained load) strengths were also achieved over this range of hydrogen levels. Except for one test at 116 ppm hydrogen, beta duplex annealing at 1950F (5 min) AC + 1100F (8 hrs) resulted in rather serious surface embrittlement or instability, although the original elongation was restored by acid pickling 0.003in from gage

TABLE 2. EFFECT OF HYDROGEN CONTENT ON 1000F CREEP-STABILITY AND ROOM-TEMPERATURE NOTCH TENSILE AND NOTCH-RUPTURE PROPERTIES OF Ti-8Al-1Mo-1V SHEET
(M-9519, A-3713 Sheet No. 3, 0.062in, longitudinal specimens originally mill annealed 1350F (8 hrs). Creep-stability exposure: 1000F-25 Ksi-150 hrs)

Heat Treatment	H_2(1) ppm	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	H_2(2) ppm	NTS(3) Ksi	NR(4) Stress Ksi	NR(4) Time Hrs
Vacuum Annealed at 1350F + 1450F (4 hrs) FC to 1000F(7)	120	Not Exp.	150.0	137.5	18.5	-	-	160	0.25
	121	1.78	157	144	16(5)	112	152	150	0.05
	-	1.05	154	138	16(6)	-	-	-	-
1450F (4 hrs) FC to 1000F(7)	-	Not Exp.	149.5	138	17.5	-	154	140	5.00
	110	1.94	156	143	17(5)	114	159	160	0.25
	-	1.24	156	141	16(6)	-	-	-	-
Hydrogenated at 1350F + 1450F (4 hrs) FC to 1000F(7)	-	Not Exp.	150.5	138.5	19	-	-	160	1.83
	112	2.03	157	142	13(5)	108	169	160	0.06
	-	1.45	156	141	21(6)	-	-	-	-
Hydrogenated at 1350F + 1450F (4 hrs) FC to 1000F(7)	-	Not Exp.	150	139	18.5	-	-	170	0.05
	127	2.06	157	143	16(5)	112	151	150	5.00
	-	1.76	157	140	19(6)	-	-	-	-
Hydrogenated at 1350F + 1450F (4 hrs) FC to 1000F(7)	234	Not Exp.	149.5	138	20	-	162	170	0.03
	129	1.60	155	139	14(5)	130	157	160	0.20
	-	1.38	154	137	20(6)	-	-	-	-
Hydrogenated at 1350F + 1450F (4 hrs) FC to 1000F(8)	222	Not Exp.	151.6	137.7	18	-	179	170	0.08
	197	0.93	148.1	144.1	4(5)	-	-	-	-
Hydrogenated at 1350F + 1450F (4 hrs) FC to 1000F(8)	308	Not Exp.	151.8	136.3	20	-	181	170	2.0
	270	1.28	149.2	143.2	2(5)	-	-	-	-

(Continued)

TABLE 2. (Continued)

Heat Treatment	H_2 (1) ppm	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	H_2 (2) ppm	NTS (3) Ksi	NR (4) Stress Ksi	NR (4) Time Hrs
Vacuum Annealed at 1350F +	122	Not Exp.	156.5	142	17.5	-	175	170	0.02
1450F (4 hrs) FC to 1000F +	118	0.50	159	145	15(5)	127	171	160	5.00
1800F (5 min) AC to 1100F	-	0.53	160	146	19(6)	-	-	-	-
(8 hrs) (7)									
1450F (4 hrs) FC to 1000F +	-	Not Exp.	155	140.5	15	-	-	170	0.07
1800F (5 min) AC + 1100F	121	0.60	158	144	11(5)	116	177	160	3.67
(8 hrs) (7)	-	0.70	163	144	18(6)	-	-	-	-
Hydrogenated at 1350F +	-	Not Exp.	155	140	17.5	-	179	170	0.08
1450F (4 hrs) FC to 1000F +	-	0.64	159	146	15(5)	134	165	170	0.41
1800F (5 min) AC + 1100F	136	0.80	160	143	16(6)	-	-	-	-
(8 hrs) (7)									
Hydrogenated at 1350F +	-	Not Exp.	155.5	140.5	16	-	163	160	5.00
1450F (4 hrs) FC to 1000F +	128	0.72	160	145	10(5)	125	162	170	0.03
1800F (5 min) AC + 1100F	-	0.59	161	147	15(6)	-	-	-	-
(8 hrs) (7)									
Hydrogenated at 1350F +	128	Not Exp.	153.5	137	19	-	176	170	0.50
1450F (4 hrs) FC to 1000F +	124	0.89	160	144	15(5)	132	167	170	0.23
1800F (5 min) AC + 1100F	-	0.70	161	144	18(6)	-	-	-	-
(8 hrs) (7)									
Hydrogenated at 1350F +	231	Not Exp.	156.9	141.3	13	-	178	170	1.17
1450F (4 hrs) FC + 1000F +	200	0.55	153.0	146.3	1(5)	-	-	-	-
1800F (5 min) AC + 1100F									
(8 hrs) (8)									
Hydrogenated at 1350F +	303	Not Exp.	156.9	142.2	11.0	-	186	170	3.20
1450F (4 hrs) FC to 1000F +	270	0.52	158.4	147.1	4(5)	-	-	-	-
1800F (5 min) AC + 1100F									
(8 hrs) (8)									

(Continued)

TABLE 2. (Continued)

Heat Treatment	H_2 (1) ppm	Creep Def, %	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	H_2 (2) ppm	NTS (3) Ksi	NR (4) Stress Ksi	NR (4) Time Hrs
Vacuum Annealed at 1350F +	141	Not Exp.	148	133	3	-	157	160	0.33
1450F (4 hrs) FC to 1000F +	130	0.11	157	148	2(5)	150	141	150	0.61
1950F (5 min) AC + 1100F	-	0.10	155	140	10(6)	-	-	-	-
(8 hrs) (7)									
1450F (4 hrs) FC to 1000F +	-	Not Exp.	153	134.5	7	-	157	160	0.03
1950F (5 min) AC + 1100F	116	0.12	160	145	5(5)	150	160	140	5.00
(8 hrs) (7)	-	0.11	163	147	7(6)	-	-	-	-
Hydrogenated at 1350F +	-	Not Exp.	153.5	135	10	-	161	160	0.08
1450F (4 hrs) FC to 1000F +	146	0.10	144	-	1(5)	127	158	160	0.07
1950F (5 min) AC + 1100F	-	0.15	160	142	8(6)	-	-	-	-
(8 hrs)									
Hydrogenated at 1350F +	-	Not Exp.	155.5	135	11.5	-	168	150	3.50
1450F (4 hrs) FC to 1000F +	133	0.12	149	147	1(5)	135	160	150	0.11
1950F (5 min) AC + 1100F	-	0.04	156	138	10(6)	-	-	-	-
(8 hrs) (7)									
Hydrogenated at 1350F +	153	Not Exp.	156	135.5	7.5	-	155	150	5.00
1450F (4 hrs) FC to 1000F +	145	0.10	148	142	1(5)	124	157	160	0.02
1950F (5 min) AC + 1100F	-	0.11	158	138	10(6)	-	-	-	-
(8 hrs) (7)									

(1) Hydrogen analysis of indicated individual tensile and/or creep-stability specimen.
(2) Hydrogen analysis of indicated individual notch rupture specimen.
(3) Notch tensile strength; 0.5in gage width, 0.25in notch width, 0.010in notch radius, and $K_t = 4.2$.
(4) Notch rupture test using same specimen configuration as (3); failed at time and stress level indicated except for those listed as 5.00 hours. In these instances, the specimen withstood 5 hours at stress noted. All other specimens satisfactorily passed 10 Ksi lower stress prior to loading and failing in less than 5 hours.
(5) Tensile tested at room temperature after creep exposure without surface pickling or conditioning.

(Continued)

TABLE 2. (Continued)

(6) Acid pickled 0.003in from gage after creep exposure but prior to tensile testing at room temperature.

(7) Anodically pickled 0.002-0.003in after heat treatment and machining to a high surface polish; no indication of machine tool marks or surface contamination.

(8) Acid pickled after heat treatment but before machining. Test results and visual examination of specimens showed that machine tool marks on milled edges developed shallow cracks and that some surface contamination also remained on most of the samples.

after 1000F creep exposure. As beta duplex annealed, the yield strength was 133-135 Ksi, but after creep exposure the yield strength increased to 145-148 Ksi, indicating that some strengthening reaction is operative under stress at 1000F. Somewhat lower notch tensile and notch rupture strengths were observed in the beta duplex annealed material compared to the alpha-beta duplexing treatment. Although not recommended at this time for Ti-8Al-1Mo-1V sheet, the beta duplex annealing treatment appears to tolerate less hydrogen; therefore, in this condition the hydrogen should be limited to 100-120 ppm.

In general the creep resistance values agreed quite well with those reported previously on similarly treated specimens(1). The creep resistance improved markedly as the annealing temperature was raised from 1450F to 1950F. However, over the limited available range of hydrogen contents, no consistent trend of creep deformation with hydrogen level was detected.

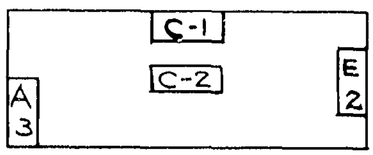
Although this program could have provided considerably more information on the effect of hydrogen at levels higher than 135 ppm, it did show that hydrogen of this magnitude had no adverse effect on 1000F creep-stability or room-temperature notch properties. Earlier work had also indicated that 1400-1450F mill annealed and 1800F (5 min) AC + 1100F (8 hrs) duplex annealed Ti-8Al-1Mo-1V sheet (sheet S-1807 from M-9519) was stable at a hydrogen content of 160 ppm(5,6). Therefore, it is concluded that for both annealed conditions, 150 ppm hydrogen is a safe level in Ti-8Al-1Mo-1V sheet and is being recommended as part of the automatic release property specifications for this composition.

Property Uniformity Within Mill Annealed Ti-8Al-1Mo-1V Sheet

In a study comparable to that performed on earlier sheets of Ti-8Al-1Mo-1V(5), a typical 0.062in sheet was selected from V-1552 for measurement of uniformity of properties throughout the sheet. The material was mill annealed at 1450F (8 hrs) and is representative of the Ti-8Al-1Mo-1V sheets being produced on the contract. Properties included in this investigation are room temperature tensile and bend tests, 800 and 1000F tensile tests, and creep-stability at 800, 900, and 1000F. Specimens were cut from four 9 x 18in locations in the sheet with the sampling plan and results as listed in Tables 3 and 4. Both longitudinal and transverse tests were conducted at room temperature, but since the strength was somewhat lower in the transverse direction, elevated-temperature and creep-stability tests were made in this direction only. However, duplicate longitudinal tensile specimens from this same sheet were tested at temperatures from 200-1000F with results presented in Table 5.

TABLE 3. UNIFORMITY OF TENSILE AND BEND PROPERTIES THROUGHOUT A TYPICAL SHEET OF Ti-8Al-1Mo-1V
(V-1552B, A-6213 Sheet No. 2, 0.056 x 36 x 90in; Finish rolled from 1800F and mill annealed at 1450F for 8 hrs)

Sheet Location (1)	Test Temp, F	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	Modulus of Elasticity, 10^3 Ksi	MBR, (2) T
A-3	RT	L	158.3	144.2	17.5	18.8	2.5
	RT	T	143.7	136.4	14.0	17.3	2.5
C-1	RT	L	156.0	144.0	17.5	17.9	2.5
	RT	T	149.1	137.1	15.5	18.1	2.5
C-2	RT	L	158.1	142.0	16.5	18.5	2.5
	RT	T	147.1	138.1	17.5	17.0	2.5
E-2	RT	L	156.5	144.0	19.0	18.8	2.5
	RT	T	146.5	137.7	16.5	17.4	2.5
A-3	800	T	102.2	86.2	13.0	13.5	-
	1000	T	84.3	71.2	20.0	10.1	-
C-1	800	T	107.1	89.8	13.0	14.5	-
	1000	T	86.1	71.8	22.0	11.5	-
C-2	800	T	105.9	89.7	12.0	13.6	-
	1000	T	85.5	70.0	21.0	10.6	-
E-2	800	T	102.9	87.4	13.0	14.5	-
	1000	T	84.9	71.0	22.0	11.9	-

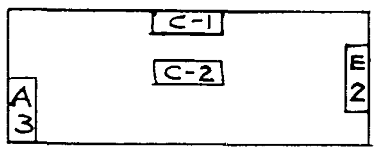


(1) Sampling plan to obtain 9 x 18in panels.
(2) Minimum press brake bend radius at 20X inspection.

TABLE 4. CREEP-STABILITY PROPERTIES OF A TYPICAL SHEET OF MILL ANNEALED Ti-8Al-1Mo-1V
(V-1552B, A-6213 Sheet No. 2; Finish rolled from 1800F and mill annealed at 1450F for 8 hrs; transverse specimens)

Sheet (1) Location	O_2 %	H_2 ppm	Creep-Stability Exposure Temp F	Stress Ksi	Time Hrs.	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
A-3			800	65	150	0.46	146.9	130.8	16.5
			900	45	150	1.30	150.3	134.6	13.5
	0.082	86	1000	25	150	2.22	151.4	138.9	16.0
			1000	25	150	2.85	153.1	141.6	6.0 (3)
C-2	0.079	105	800	65	150	0.54	141.5	132.8	2.0
			900	45	150	0.93	151.6	133.4	14.0
	0.100	99	1000	25	150	2.80	150.2	139.6	4.0
			1000	25	150	3.11	152.9	140.5	15.0 (2)

(1) Sampling plan to obtain four 9 x 18in panels.



(2) Acid pickled 0.003in from gage after exposure; all others tensile tested as exposed with no surface conditioning.
(3) Broke at end of gage length.

TABLE 5. ELEVATED-TEMPERATURE TENSILE PROPERTIES OF MILL ANNEALED Ti-8Al-1Mo-1V SHEET
(V-1552B, A-6213 Sheet No. 2, 0.056 x 36 x 90in, mill annealed at 1450F for 8 hrs; averages of duplicate tests)

Test Temp,F	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	Modulus of Elasticity 10^3 Ksi
RT	L	157.2	143.6	17.6	18.5
RT	T	146.6	137.3	15.9	17.5
200	L	149.0	132.3	15.5	17.8
400	L	134.3	115.1	15.0	17.0
600	L	124.4	102.1	12.5	16.2
800	L	114.4	94.3	12.0	14.7
1000	L	92.9	75.1	16.0	12.2

Except for the transverse yield strength in Panel A-3 (single specimen results), the room-temperature properties were quite uniform throughout the sheet. Likewise, the elevated temperature strengths did not exhibit any substantial variation, with the transverse yield strengths falling in the ranges of 87-90 Ksi and 71-72 Ksi at 800 and 1000F, respectively. As shown in Table 5, the longitudinal strengths at 800 and 1000F were about 5 Ksi higher than the transverse values in Table 3. Elastic modulus data are also listed in Tables 3 and 5 showing that the modulus was somewhat higher in the longitudinal direction.

Creep-stability test results were obtained from Panels A-3 and C-2, only, since it was felt that any differences between these two areas in the sheet would be sufficient to establish the variability in creep and stability properties of the material. As shown in Table 4, the creep resistance values in the two sheet locations were not greatly different, although the deformation at the center of the sheet (C-2) was somewhat higher at 800 and 1000F than the corner (A-3). Comparing these values with those listed in Table 5 of the Eleventh Bimonthly Report[3], it is seen that the latter creep deformation data for 1450F (4 hrs) mill annealed sheet were slightly lower than those in Table 4 of this report. One apparent reason for this is that the previous tests were in the longitudinal direction which exhibited nearly 10 Ksi higher yield strength than the transverse specimens in Table 4.

Good stability was observed in samples from Panel A-3 with one test breaking at the end of the gage length and thus producing a low elongation value. However, two specimens in Panel C-2 exhibited rather low levels of ductility; reasons for this are not readily apparent. It is difficult to understand why the sample exposed at 800F should show such low elongation, while good stability was indicated for the specimen exposed at 900F. Since most of the tests in this sheet did not exhibit any serious ductility losses, it is concluded that no metallurgical stability problem exists at 800-1000F in Ti-8Al-1Mo-1V sheet mill annealed at 1450F (8 hrs), although some indication of surface instability is present, particularly at 1000F.

Stress Relieving Studies on Welded Ti-8Al-1Mo-1V Sheet

This study was initiated to expand on the data generated earlier on welded Ti-8Al-1Mo-1V sheet[6] and was designed to determine the temperatures and times required to stress relieve

unwelded sheet and then ascertain the effect of two of the more promising stress relieving cycles on the properties of welded material. The same sheet which was used for the property uniformity investigation, as described in the preceding section, was utilized for this program.

Stress relief measurements were made on the parent metal using a procedure which has been successfully applied in previous work; i.e., relaxation of restrained bend specimens as a practical indication of the amount of stress relief. Longitudinal bend samples, 3/4 x 5in, were sheared from the 0.056in sheet of Ti-8Al-1Mo-1V (V-1552B) and press brake bent around a 5T radius to 130° before springback (50° included angle between the two legs of the bend specimen). The bent samples were then placed in a V-shaped trough constructed of two plates of stainless steel welded together to form a 50° angle, as shown schematically in Figure 1, and held in place by means of a bolted 9/16in diameter tie-down bar. Prior to the stress relief treatments, the specimens were removed, the internal angle of each was measured without restraint (this was normally 70-80°), and then the samples again bolted in place in the V-shaped fixture.

Heating cycles consisted of placing the loaded fixture in a heated furnace, 900-1300F, for times which varied from 0.25 to 90 hours. Upon completion of a given cycle, the fixture was removed from the furnace, cooled, and the bend samples removed from the fixture for angle measurement. Specimens designated for 0.25, 0.5, and 1.0 hour heating periods were used only once, while those for longer times were re-loaded and re-heated at the given temperature. The percent relaxation in each case was calculated by dividing the difference between the initial and final angles by the initial angle less 50°, and multiplying this quotient by 100. Thus, as a sample relaxed to the point where the angle remained at 50° after removal from the fixture, it was considered to be 100 percent stress relieved.

Results of these tests for the as-mill annealed and duplex annealed Ti-8Al-1Mo-1V sheet are illustrated in Figures 2 and 3, respectively, and show that for the shorter times at 900 and 1000F, duplex annealed material stress relieved faster than the mill annealed specimens. However, at 1100 and 1200F, more stress relief was exhibited in a given time for mill annealed sheet. At 1300F, there was no difference between the two conditions.

Thus, to achieve substantially complete stress relief and utilize short practical periods, it is seen that only

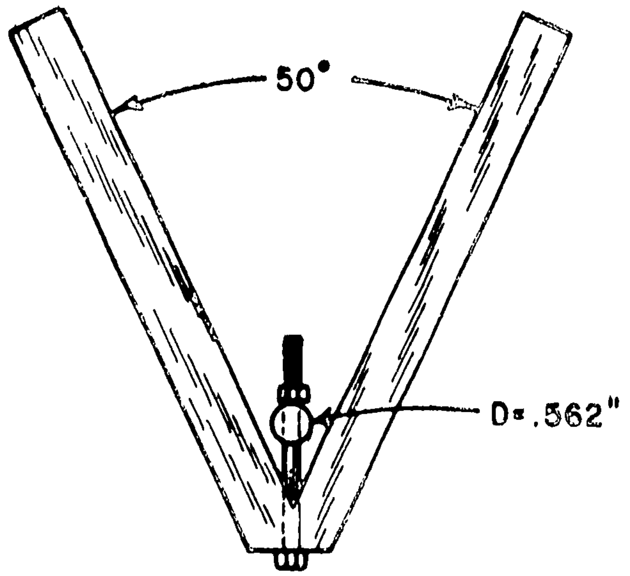


FIGURE 1. SCHEMATIC OF V-SHAPED FIXTURE TO RESTRAIN BEND SPECIMENS FOR STRESS RELAXATION MEASUREMENTS.

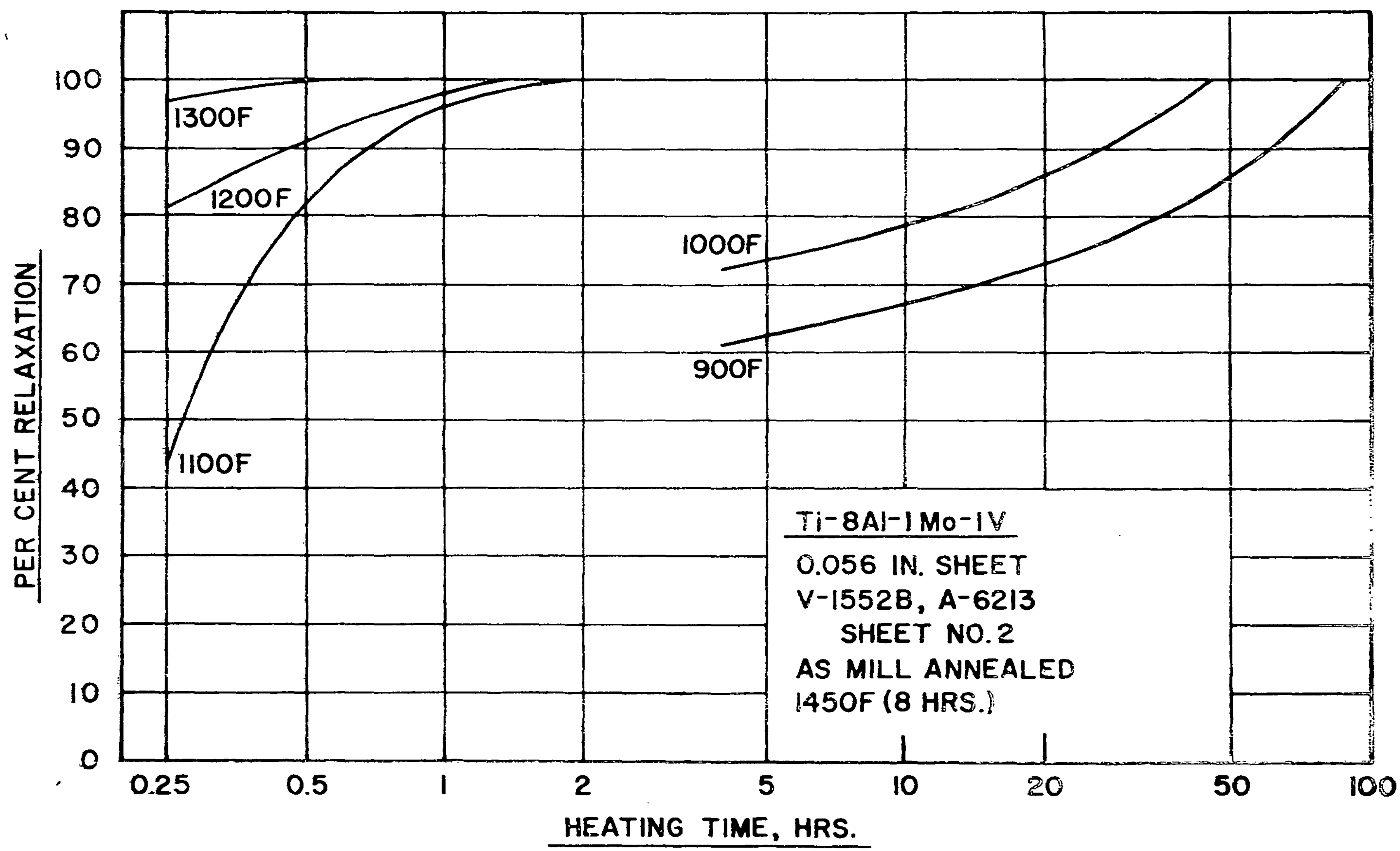


FIGURE 2. EFFECTS OF HEATING TIME AND TEMPERATURE ON THE RELAXATION OF RESTRAINED BEND SPECIMENS OF MILL ANNEALED Ti-8Al-1Mo-1V SHEET.

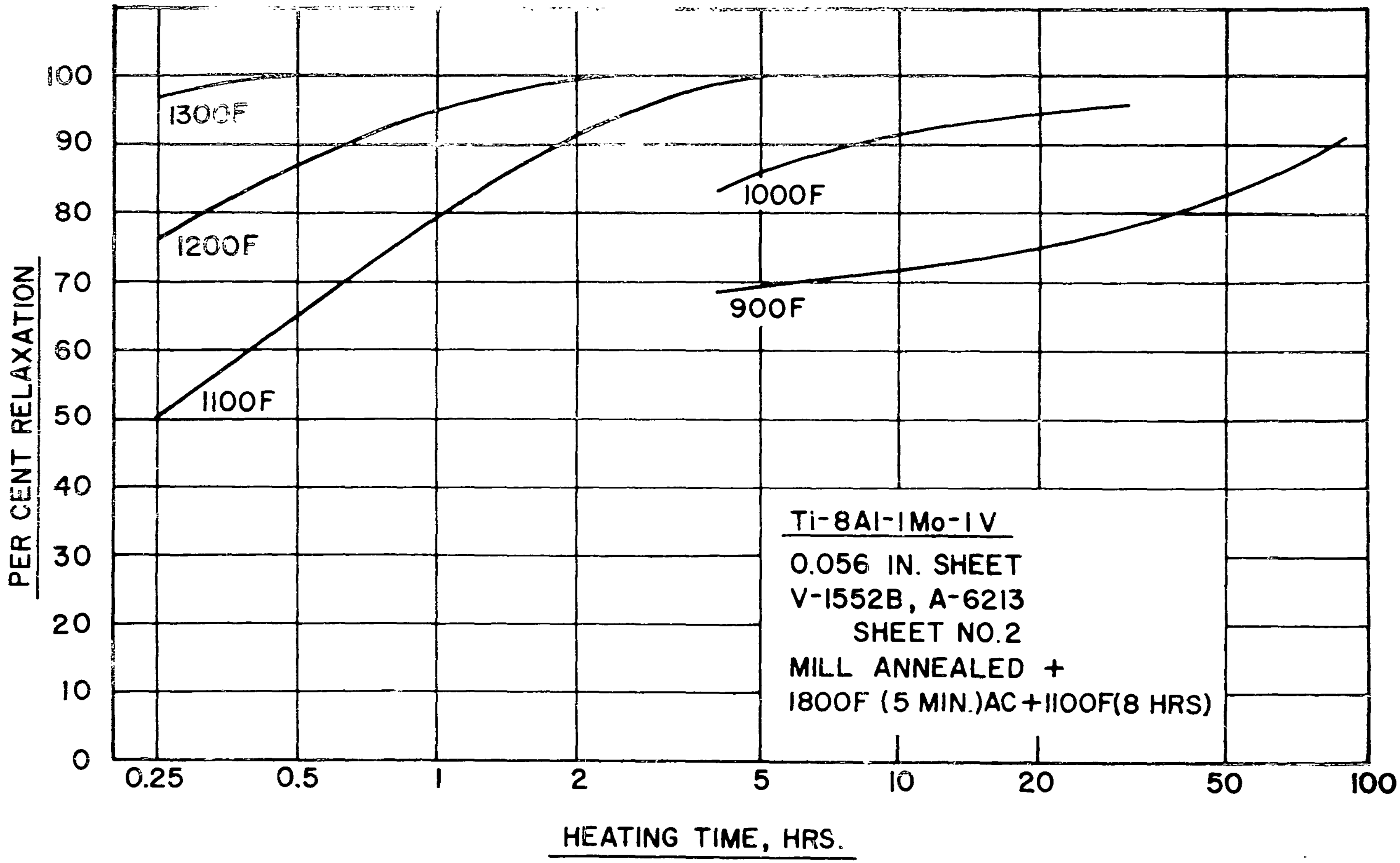


FIGURE 3. EFFECTS OF HEATING TIME AND TEMPERATURE ON THE RELAXATION OF RESTRAINED BEND SPECIMENS OF DUPLEX ANNEALED Ti-8Al-1Mo-1V SHEET.

cycles at 1100-1300F are of interest. Selection of two extreme, but yet practical, treatments for further study in both annealed conditions is as follows:

Mill Annealed (1450F - 8 hrs)	Duplex Annealed (1800F (5 min) AC + 1100F (8 hrs))
1100F (2 hrs)	1100F (5 hrs)
1300F (1/2 hr)	1300F (1/2 hr)

Welded specimens have been given these treatments to determine the effect of each on the welded properties. However, this phase of the investigation is incomplete and, consequently, the data will be included in the Summary Report.

In a corollary study, bend specimens were coated with salt and given a stress relieving treatment to determine if stress corrosion cracking occurred. Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr were also included in this study; therefore, for comparison purposes, results on all three alloys are described in a later section of this report.

PROCESSING OF Ti-8Al-1Mo-1V

Finishing operations on half of the sheets from the five 1600-pound ingots of Ti-8Al-1Mo-1V, which have been described in previous reports(3,7), were completed and these sheets were tested and inspected during this period. Of the original 46 sheets in process, 42 reached final testing and inspection with the ranges of tensile and bend properties listed in Table 6. Based on the test results from this rather substantial number of sheets, the following property specification was recommended to the Navy Bureau of Weapons for mill annealed Ti-8Al-1Mo-1V sheet:

UTS Ksi	YS(0.2%) Ksi	Elong (2in),%	Min Bend Radius,T	H_2 ppm
140 min	130 min	10 min	4.0 max	150 max

This specification was accepted and will be used for automatic release of Ti-8Al-1Mo-1V sheets to be shipped on the contract.

As indicated in an earlier section of this report, the Navy Bureau of Weapons requested that no Ti-8Al-1Mo-1V sheets

TABLE 6. RANGES OF ROOM-TEMPERATURE TENSILE AND BEND PROPERTIES OF 42 SHEETS OF Ti-8Al-1Mo-1V MILL ANNEALED AT 1450F (8 HOURS)

Gage in	No. of Sheets	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	MBR, T	H_2 ppm
0.020	8	141.6 - 154.1	133.3 - 145.4	13.5 - 20.0	3.0	60 - 90
0.040	12	141.9 - 161.9	131.8 - 148.9	12.0 - 17.0	3.1 - 3.8	50 - 160*
0.062	8	143.6 - 156.8	133.8 - 145.0	11.5 - 17.5	3.1 - 3.5	50 - 150
0.090	7	141.4 - 156.1	134.3 - 147.7	14.5 - 17.0	2.9 - 3.3	50 - 130
0.125	7	147.2 - 154.8	139.3 - 146.1	12.0 - 18.0	3.0 - 4.0	30 - 40

* Only one sheet analyzed 160 ppm hydrogen; all others were 150 ppm or less.

be duplex annealed, since there has been no demand for material in this condition. Therefore, the remaining half of the sheets (a total of 46) from the five 1600-pound heats (V-1551-V-1555), which had previously been mill annealed at 1450F (8 hrs) and rough ground, is being finish ground, pickled, and tested as mill annealed with completion scheduled for July, 1961. If, at some future date, duplex annealed material is required, any of these sheets can be so treated, although the resultant final gage after subsequent finishing operations will be 0.004-0.006in less than before duplex annealing.

As the alloys being produced in the contract were designed for superior elevated-temperature properties, the recommendation was accepted that tensile testing be performed at 800F. To determine the extent of a correlation between strengths at room temperature and 800F, it was agreed that approximately 25 percent of the Ti-8Al-1Mo-1V sheets whose room-temperature yield strengths were 135 Ksi or greater would be tested at 800F, while 100 percent testing, wherever possible, would be conducted at 800F on material possessing room-temperature yield strengths less than 135 Ksi. These tests are currently being made in the lowest-strength direction of sheets of the five gages. At a later date, the need for an elevated-temperature property specification will be ascertained. However, because Contract NOas-59-6227-c is nearing completion, the 800F data can be used only for design allowables and not to establish an automatic release for sheets on the contract.

Initial processing of the last ingot of Ti-8Al-1Mo-1V (V-1848), along with a few remaining sheet bars from the first five heats, was described in the Eleventh Bimonthly Report [(3)] in which slabs were pressed, conditioned, chemically analyzed, and sheet processing scheduled. In this period sheet bars were rolled from 1880-1900F to an intermediate stage, conditioned, vacuum outgassed at 1350F, and finish rolled from 1800F. All operations proceeded without difficulty; the 32 rolled sheets will be mill annealed at 1450F (8 hrs) early in July with finish processing scheduled for completion in August, 1961.

The general status of all Ti-8Al-1Mo-1V sheets in the production phase of the contract is summarized below:

Status of Ti-8Al-1Mo-1V Sheets

Gage, in	No. of Sheets Ordered	No. of Sheets in Process	No. of Sheets Completed	Navy-Approved Customer Orders*	
				No. of Sheets Ordered	No. of Sheets Shipped
0.020	27	36	8	9 1/2	4
0.040	20	29	12	16	5 1/2
0.062	18	26	8	6 1/2**	1**

(Continued)

Status of Ti-8Al-1Mo-1V Sheets (Continued)

Gage, in	No. of Sheets Ordered	No. of Sheets in Process	No. of Sheets Completed	Navy-Approved Customer Orders* No. of Sheets Ordered	Navy-Approved Customer Orders* No. of Sheets Shipped
0.090	15	17	7	2 1/2	1
0.125	14	16	7	2 1/2	0
Total	94	124	42	37	11 1/2

* Equivalent of 36 x 96in sheets

** Includes one sheet used for evaluation of uniformity of properties and welding studies.

Properties of the mill annealed Ti-8Al-1Mo-1V sheets shipped are listed in Table 7. It is estimated that processing of all of the sheets listed in the above general status will be completed by August 31 and that material for the remaining individual customer orders will also be shipped by that date.

EVALUATION OF Ti-5Al-5Sn-5Zr AND Ti-7Al-12Zr SHEET

A number of laboratory studies were continued or completed on Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheet to investigate and evaluate more thoroughly the properties of the two alloys. Included were a study of processing contamination, determination of the effect of hydrogen on creep-stability and notch properties, an additional investigation of the effects of annealing time and cooling rate on tensile and creep-stability properties, evaluation and determination of properties at various temperatures, stress relief studies on welded sheet material, and a limited investigation of the stress corrosion behavior of both compositions. Results of these studies are described in the sections to follow.

Process Contamination Studies

As indicated in the Eleventh Bimonthly Report(3), a 13in long panel was cut from the end of one sheet of each gage and alloy being processed from the balance of the first two ingots, V-1540 and V-1541. Properties of these fully processed sheets are listed in a later section of this report; however, these six panels had been mill annealed at 1350F (8 hrs) and then surface ground to remove about 0.006-0.008in from gage (0.003-0.004in

TABLE 7. TENSILE AND BEND PROPERTIES OF Ti-8Al-1Mo-1V SHEETS SHIPPED TO NAVY-APPROVED CUSTOMERS
(Mill annealed at 1450F for 8 hours)

Customer	Gage in	Heat No.	Test No.	Sheet No.	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	MBR, T	H_2 ppm
Convair - San Diego	0.020	V-1551T	A-6495	1	L	145.9	135.9	20.0	3.0	80
					T	144.0	137.4	14.5	3.0	-
				5	L	154.1	145.4	17.0	3.0	90
					T	149.3	142.3	14.0	3.0	-
				7	L	152.8	145.0	15.0	3.0	60
					T	151.0	141.6	13.5*	3.0	-
				8	L	152.2	144.1	12.5*	3.0	70
					T	149.1	141.7	15.5	3.0	-
Convair - San Diego	0.040	V-1551M	A-6506	2	L	151.1	145.0	15.0	3.3	50
					T	145.9	139.3	14.0	3.1	-
				3	L	151.4	144.3	10.0*	3.3	60
					T	146.0	137.3	15.5	3.1	-
				5	L	153.5	143.2	15.0	3.3	60
					T	144.9	138.7	16.0	3.3	-
				6	L	159.8	149.4	16.5	3.1	60
					T	-	-	-	-	-
				7	L	155.4	145.0	17.0	3.1	70
					T	146.8	136.7	13.0	3.1	-
Boeing - Seattle	0.040	V-1551M	A-6506	4	L	158.4	146.8	14.0	3.1	60
					T	143.0	139.1	15.5	3.1	-
TMCA (Evaluation	0.062	V-1552B	A-6213	2	L	156.8	145.0	15.0	3.2	130
on Contract NOas 59-6227-c					T	144.0	137.2	12.0*	3.2	-
Convair - San Diego	0.090	V-1554T	A-6214	4	L	-	-	-	3.1	70
					T	145.5	137.1	17.0	3.5	-

* Broke at end of gage length.

from each side). These as-ground panels, along with the initial 1750F rolled sheets from the two heats (also as-mill annealed at 1350F for 8 hrs, but then finish ground and pickled), were used for the contamination studies.

Bend and tensile specimens were sheared from the 12 sheets and the tensile specimens were tested as received with no additional heat treatment or surface pickling. The bend samples were tested as received and after acid pickling nominally 0.002, 0.004, and 0.006in from the gage. In addition, tensile, bend, and stability specimens were prepared from the 0.062in panel (as mill annealed-and-ground) of each alloy after acid pickling an aim of 0, 0.003, 0.006, and 0.009in from gage and then annealing at 1650F (1/2 hr) AC in sealed cover sheets of commercially pure titanium. Finally, in this phase of the investigation, small coupons from the 12 sheets were heated at 1800 and 1820F for 30 minutes and water quenched, with and without prior acid pickling 0.010in from gage, and examined metallographically for differences in depth of surface contamination. Samples from the two 0.062in as-ground panels were also used to study metallographically the depth of contamination obtained during annealing at 1650F for 0.5 and 2 hours and to determine if any of the available protective coatings offered worthwhile protection from oxygen contamination during annealing at 1650F (1/2 hr) AC.

Results of tensile and bend tests after acid pickling various amounts from the 12 sheets are listed in Table 8 in which all samples were tested in the 1350F (8 hrs) mill annealed condition. All 12 sheets had been surface ground to remove approximately 0.006-0.007in from the gage of each; however, six of them (A-4798 through A-4814) had been acid pickled during mill processing to remove 0.001-0.002in from gage and, therefore, were substantially free of grind lines. The other six panels (S-3790 through S-3796) had been surface ground only with no pickling.

As shown in Table 8, metal removal by pickling improved the bendability of most of the sheets, particularly those that had been received as-ground. To achieve a plateau in the minimum bend radius (beyond which the bendability was nearly constant with increased pickling) or to reach a reasonably high level of bend ductility, total metal removal of 0.007-0.012in from gage was required in each alloy (grinding + pickling). Some portion of the increase in bendability with pickling of the as-ground panels probably resulted from removing a thin cold worked surface after grinding. However, as the tensile properties indicate, no pronounced loss in tensile elongation was apparent from tests of as-ground material in either direction.

TABLE 8. **EFFECT OF ACID PICKLING ON THE TENSILE AND BEND PROPERTIES OF Ti-5Al-5Sn-5Zr AND Ti-7Al-12Zr SHEETS**
(Finish rolled from 1750F, mill annealed at 1350F for 8 hours, and surface finished as indicated)

Sheet No.	Gage in	Gage Removed After Hot Rolling, in	Additional Gage Removed By Laboratory Pickling, in	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	MBR T (1)
Ti-5Al-5Sn-5Zr (V-1540)								
A-4812(2)	0.020	0.009	None	L				5.4
(0.081% O_2, 45ppm H_2)			0.002	L				3.2
			0.004	L				3.7
(Beta Transus 1800-1820F)			0.006	L				4.5
A-4801(2)	0.062	0.008	None	L				3.2
(0.072% O_2, 35 ppm H_2)			0.002	L				7.3(3)
			0.004	L				4.3
(Beta Transus 1800-1810F)			0.006	L				5.0
A-4814(2)	0.090	0.009	None	L				3.9
(0.072% O_2, 30 ppm H_2)			0.002	L				3.3
			0.004	L				3.3
(Beta Transus 1810-1820F)			0.006	L				3.3
S-3792	0.020	0.007	None	L	142.4	132.5	15.5	6.0(6)
(0.087% O_2, 156 ppm H_2)			None	T	140.9	133.5	16.8	-
			0.001	L				5.0
			0.004	L				4.8
(Beta Transus 1800-1820F)			0.005	L				3.7
S-3790	0.062	0.008	None	L	130.2	123.5	19.3	5.0(4)
(0.07% O_2, 88 ppm H_2)			None	T	129.9	123.2	18.5	-
			0.003	L				3.3
			0.005	L				5.0(3)
(Beta Transus <1800F)			0.007	L				3.3

(Continued)

TABLE 8. (Continued)

Sheet No.	Gage in	Gage Removed After Hot Rolling, in	Additional Gage Removed By Laboratory Pickling, in	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	MBR T (1)
S-3796	0.090	0.007	None	L	134.4	127.9	16.5	3.1(4)
(0.07% O_2, 67 ppm H_2)			None	T	132.9	125.3	16.8	-
			0.002	L				3.6
			0.003	L				3.4
(Beta Transus <1800F)			0.005	L				3.4
Ti-7Al-12Zr (V-1541)								
A-4798(2)	0.020	0.005	None	L				3.7
(0.109% O_2, 78-90 ppm H_2)			0.001	L				3.7
			0.004	L				3.2
(Beta Transus >1820F)			0.006	L				3.2
A-4802(2)	0.062	0.007	None	L				5.0
(0.091% O_2, 35-41 ppm H_2)			0.002	L				4.3
			0.004	L				5.0
(Beta Transus 1820-1830F)			0.006	L				5.1
A-4809(2)	0.090	0.007	None	L				3.5
(0.073% O_2, 32-40 ppm H_2)			0.002	L				4.0
			0.004	L				4.0
(Beta Transus 1820 - 1830F)			0.006	L				4.0
S-3795	0.020	0.007	None	L	144.2	133.7	16.3	6.0(4)
(0.12% O_2, 38 ppm H_2)			None	T	146.8	136.9	13.8	-
			0.002	L				3.7
			0.003	L				3.7
(Beta Transus 1800-1820F)			0.005	L				3.0

(Continued)

TABLE 8. (Continued)

Sheet No.	Gage in	Gage Removed After Hot Rolling, in	Additional Gage Removed By Laboratory Pickling, in	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	MBR T (1)
S-3793	0.062	0.006	None	L	145.4	133.8	16.0	6.3
(0.09% O_2, 68 ppm H_2)			None	T	148.8	136.3	16.8	-
			0.002	L				3.3
			0.004	L				5.1(3)
(Beta Transus 1800-1820F)			0.006	L				4.7(3)
S-3791	0.090	0.006	None	L	140.1	134.2	17.5	3.6
(0.09% O_2, 50 ppm H_2)			None	T	142.6	134.1	17.3	-
			0.003	L				4.9
			0.006	L				3.4
(Beta Transus >1820F)			0.009	L				3.5

(1) Minimum press brake bend radius at 20X inspection.
(2) As ground + acid pickled 0.001-0.002in from gage; essentially free of grind lines. All other sheets as ground only.
(3) Smaller radii not tested because of lack of sample; therefore, not the minimum bend radius.
(4) Failed at specified bend radius.

Results of annealed tensile, bend, and stability tests, which were conducted after various amounts of pickling before annealing at 1650F (1/2 hr) AC, are presented in Tables 9 and 10 for the 0.062in ground panels of Ti-5Al-5Sn-5Zr (S-3790) and Ti-7Al-12Zr (S-3793). No improvement in properties or 1000F stability was observed on the Ti-5Al-5Sn-5Zr with increased pickling, material in which 0.008in had already been removed from the gage by grinding. Therefore, in this alloy, it appears that removal of no more than 0.008in from gage is required prior to final annealing at 1650F and perhaps a lesser amount of metal removal is tolerable.

As shown in Table 10, acid pickling of 0.006-0.010in from the gage was required to improve the annealed bendability, although tensile ductility was unaffected by this gage removal. Pickling of only 0.002in from mill annealed samples (see S-3793 in Table 8) was sufficient to provide a 3.3T bend radius, so either the 1650F annealed bend results in Table 10 were not sufficiently exhaustive to present a valid picture or the residual surface contamination diffused inward during annealing at 1650F.

In general, the stability results were poor with pickling 0.006in from gage exhibiting only fair thermal stability and inferior creep-stability properties. Additional metal removal did not improve the stability appreciably. Chemical analyses of S-3793 do not reveal abnormal interstitial level, although as shown in Table 8, the oxygen content of the as-ground material was 0.09 percent, a level somewhat higher than desired for this phase of the study. However, analyses of individual creep-stability specimens in Table 10 indicate low hydrogen and oxygen contents no higher than 0.086 percent.

As a result, conclusions regarding how much surface metal should be removed from hot rolled-and-mill annealed Ti-7Al-12Zr sheet cannot be reached from the creep-stability evaluation of this particular panel. However, it is safe to assume that it would be at least as much as Ti-5Al-5Sn-5Zr. The fact that generally good creep-stability properties have been obtained on the first 0.062in sheets of Ti-7Al-12Zr (A-4802 and A-4799), as listed in Tables 11 and 12 of the Eleventh Bimonthly Report[3] and Table 7 of the Ninth Bimonthly Report[2], both of which had been ground and pickled to remove 0.006-0.007in from gage prior to laboratory finish annealing at 1650F, indicates that surface metal removal from Ti-7Al-12Zr prior to final annealing can be limited to 0.006-0.007in.

Metallographic studies were also performed on the six ground panels of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, as outlined

TABLE 9. **EFFECT OF ACID PICKLING ON THE ANNEALED TENSILE, BEND, AND STABILITY PROPERTIES OF Ti-5Al-5Sn-5Zr SHEET**

(V-1540, Sheet S-3790, 0.062in; Finish rolled from 1750F, mill annealed at 1350F (8 hrs), ground, acid pickled as indicated, and annealed at 1650F (1/2 hr) AC).*

Gage Removed By Laboratory Pickling Prior to Annealing, in	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	MBR, T (1)
None	None	-	125.9	115.1	23.0	4.0
0.005	"	-	121.0	111.4	22.0	4.4
0.008	"	-	122.1	110.7	17.0	4.1
0.015	"	-	119.7	110.9	19.0	4.3
None	1000F - 150 Hrs	-	122.8	114.2	20.5(2)	-
"	" "	-	122.3	115.1	20.0(3)	-
"	1000F - 25 Ksi - 150 Hrs	0.021	120.0	112.6	21.0(2)	-
"	" " "	0.009	119.7	111.7	19.0(3)	-
0.005	1000F - 150 Hrs	-	123.2	115.6	19.0(2)	-
"	" "	-	122.7	114.3	20.0(3)	-
"	1000F - 25 Ksi - 150 Hrs	0.031	120.6	112.8	18.0(2)	-
"	" " "	0.012	123.2	115.6	19.0(3)	-
0.008	1000F - 150 Hrs	-	121.5	115.8	18.0(2)	-
"	" "	-	121.7	115.4	17.0(3)	-
"	1000F - 25 Ksi - 150 Hrs	0.021	122.4	114.3	21.0(2)	-
"	" " "	0.031	121.6	113.3	15.0(3,4)	-

(Continued)

TABLE 9. (Continued)

Gage Removed By Laboratory Pickling Prior to Annealing, in	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	MBR, T (1)
0.015	1000F - 150 Hrs	-	120.8	115.3	21.5(2)	-
"	" "	-	120.6	114.2	16.0(3)	-
"	1000F - 25 Ksi - 150 Hrs	0.018	118.3	108.7	14.0(2)	-
"	" " "	0.006	119.6	112.6	15.0(3,4)	-

* Panel from S-3790 had been surface ground removing 0.008in from gage after mill annealing. Longitudinal samples were then acid pickled in the laboratory as indicated, annealed at 1650F (1/2 hr) AC in sealed covers of commercially pure titanium, acid pickled 0.002in from gage, machined, and tested.

(1) Minimum press brake bend radius at 20X inspection.

(2) Tensile tested after stability exposure without any surface conditioning.

(3) Acid pickled 0.003in from gage after stability exposure, but prior to tensile testing at room temperature.

(4) Broke at end of gage length.

TABLE 10. **EFFECT OF ACID PICKLING ON THE ANNEALED TENSILE, BEND, AND STABILITY PROPERTIES OF Ti-7Al-12Zr SHEET**
(V-1541, Sheet S-3793, 0.062in; Finish rolled from 1750F, mill annealed at 1350F (8 hrs), ground, acid pickled as indicated, and annealed at 1650F (1/2 hr) AC).*

Gage Removed By Laboratory Pickling Prior to Annealing, in	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	MBR,(1) T
None	None	-	133.4	121.4	19.0	5.0
0.006	"	-	133.4	122.1	20.0	4.4
0.010	"	-	134.3	123.4	19.0	4.1
0.018	"	-	135.0	122.9	20.0	4.0
None	1000F - 150 hrs	-	140.6	131.2	9.0(2)	-
"	" "	-	140.3	130.5	15.0(3)	-
" (0.062% O_2,	1000F - 25 Ksi - 150 Hrs	0.041	137.6	128.8	(2,4)	-
" 35 ppm H_2)	" " "	0.044	134.2	129.3	1.0(3)	-
0.006	1000F - 150 Hrs	-	145.4	137.2	11.5(2)	-
"	" "	-	135.3	127.5	(3,4)	-
"	1000F - 25 Ksi - 150 Hrs	0.030	137.0	127.7	4.0(2)	-
"	" " "	0.039	138.8	126.6	10.0(3)	-
0.010	1000F - 150 Hrs	-	142.3	132.8	10.0(2)	-
"	" "	-	141.5	131.5	18.0(3)	-
" (0.086% O_2,	1000F - 25 Ksi - 150 Hrs	0.074	139.2	129.6	6.0(2)	-
" 35 ppm H_2)	" " "	0.061	128.6	128.6	1.0(3,5)	-

(Continued)

TABLE 10. (Continued)

Gage Removed By Laboratory Pickling Prior to Annealing, in	Stability Exposure	Creep Def, %	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	MBR, T (1)
0.018	1000F - 150 Hrs	-	140.6	129.6	7.5(2)	-
"	" "	-	142.9	133.3	12.0(3)	-
"	1000F - 25 Ksi - 150 Hrs	0.064	99.6	Broke before YS (2)		-
"	" " "	0.044	125.3	Broke at YS (3,4,5)		-

* Panel from S-3793 had been surface ground removing 0.006in from gage after mill annealing. Longitudinal samples were then acid pickled in the laboratory as indicated, annealed at 1650F (1/2 hr) AC in sealed covers of commercially pure titanium, acid pickled 0.002in from gage, machined and tested.

(1) Minimum press brake bend radius at 20X inspection.

(2) Tensile tested after stability exposure without any surface conditioning.

(3) Acid pickled 0.003in from gage after stability exposure, but prior to tensile testing at room temperature.

(4) Broke at end of gage length.

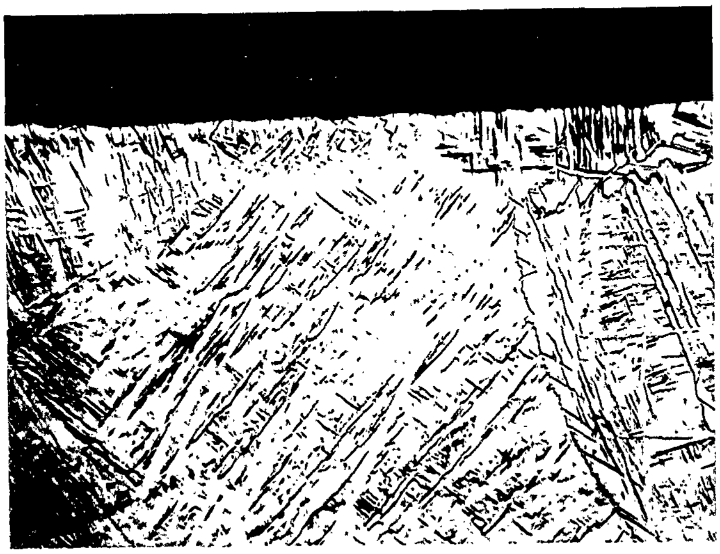
(5) Pitted pickled surface; test results questionable.

previously. Quenching small coupons from near the beta transus (1800-1820F), with and without prior pickling 0.010in from the gage of the as-ground panels, resulted in no consistent differences in the depth of contamination between the two sets of samples as determined by microscopic examination of the cross-sections. Heating at 1800F for 30 minutes did show, however, that this thermal treatment produced contamination to a depth of approximately 0.002-0.003in in Ti-5Al-5Sn-5Zr and somewhat greater in Ti-7Al-12Zr.

More conclusive results were obtained by heating samples from Panels S-3790 (Ti-5Al-5Sn-5Zr) and S-3793 (Ti-7Al-12Zr) enclosed in sealed covers of commercially pure titanium sheets. This was performed at 1820F (1/2 hr) WQ on coupons which were as-ground, pickled, and as-annealed at 1650F in air, with and without various protective coatings. Photomicrographs illustrating the more important facets of this investigation are presented in Figures 4 through 9. Figures 4 and 6 show that no residual oxygen contamination existed on the as-ground sheets of both alloys. In other words, the 0.008in and 0.006in removed by rough grinding from the gage of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, respectively, were sufficient to eliminate contamination which had occurred during prior hot rolling and annealing.

Figure 5 shows that contamination from air annealing of Ti-5Al-5Sn-5Zr at 1650F (1/2 hr) AC extended to a depth of 0.001-0.002in while the same treatment on Ti-7Al-12Zr (Figure 8) resulted in depth of major contamination of 0.0015-0.002in with isolated areas of oxygen enrichment extending to a depth of 0.003-0.004in. However, it should be noted that the 1650F air annealed samples were sealed in titanium covers without descaling and the subsequent treatment of 1820F (1/2 hr) WQ probably resulted in some diffusion inward of the oxygen-rich surface layer. As a result, the depth of contamination as measured metallographically is apt to be somewhat greater than existed after annealing at 1650F (1/2 hr) AC. Also, the particular sample in Figure 8 was quenched from very near the beta transus; consequently, small islands of alpha were stabilized at very slightly higher-than-normal oxygen contents.

Of interest in Figure 7 is a roughened zone of demarcation 0.0015-0.002in beneath the surface, a depth corresponding to the major contamination shown in Figure 8. This phenomenon was also observed in air annealed Ti-5Al-5Sn-5Zr samples, but did not occur in specimens which were annealed at 1650F in sealed covers. Although the reasons for this zone are not clear, it may be associated with the electropolishing or etching procedure in which the surface layer is harder and of a higher oxygen content than the interior material. This

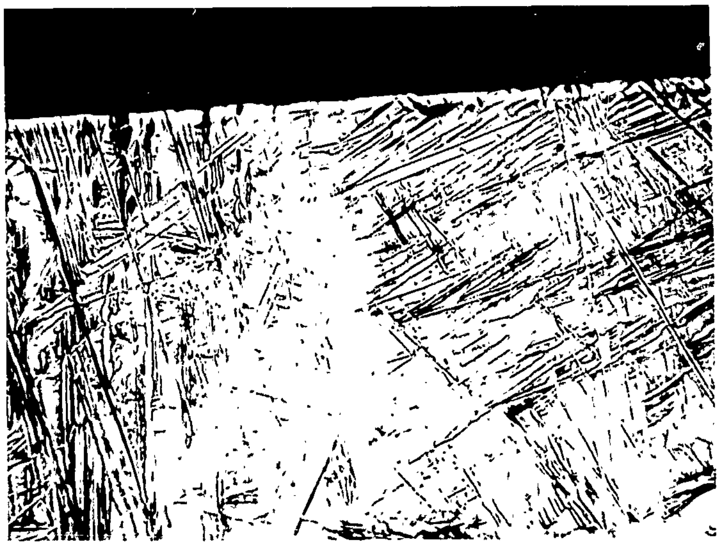


61-108-BO 250X

FIGURE 4. Ti-5Al-5Sn-5Zr, S-3790, 0.062in. AS-ROUGH GROUND + 1820F (1/2 HR) WQ IN SEALED COVERS, SHOWING THAT NO SURFACE CONTAMINATION EXISTED IN AS-GROUND MATERIAL.

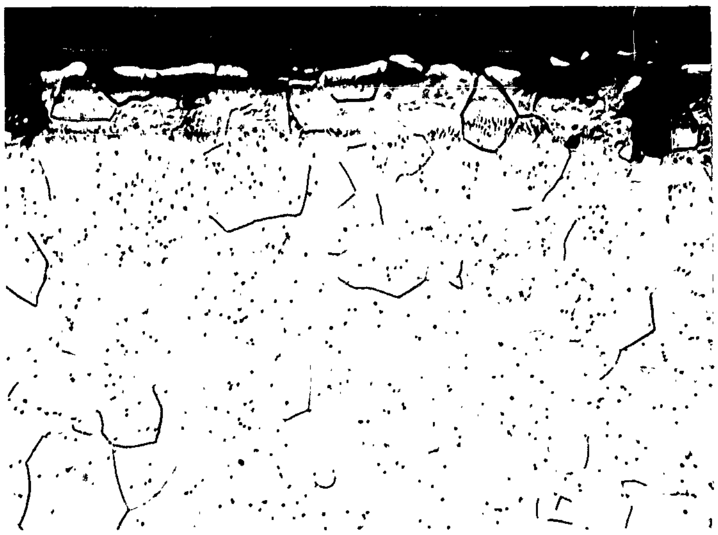
61-108-BG 250X

FIGURE 5. Ti-5Al-5Sn-5Zr, S-3790, 0.062in. AS-ROUGH GROUND + 1650F (1/2 HR) AC IN AIR + 1820F (1/2 HR) WQ IN SEALED COVERS. SURFACE CONTAMINATION FROM AIR ANNEALING AT 1650F MEASURES 0.001-0.002in IN DEPTH.



61-108-CE 250X

FIGURE 6. Ti-7Al-12Zr, S-3793, 0.062in. AS-ROUGH GROUND + 1820F (1/2 HR) WQ IN SEALED COVERS, SHOWING THAT NO SURFACE CONTAMINATION EXISTED IN AS-GROUND MATERIAL.



61-108-AQ 250X

FIGURE 7. Ti-7Al-12Zr, S-3793, 0.062in. AS-ROUGH GROUND + 1650F (1/2 HR) AC IN AIR. NOTE ROUGHENED-APPEARING ZONE OF DEMARCATION 0.0015-0.002in BELOW SURFACE OF SHEET.

61-108-BW 250X

FIGURE 8. Ti-7Al-12Zr, S-3793, 0.062in. AS-ROUGH GROUND + 1650F (1/2 HR) AC IN AIR + 1820F (1/2 HR) WQ IN SEALED COVERS. MAJOR SURFACE CONTAMINATION FROM AIR ANNEALING AT 1650F MEASURES 0.0015-0.002in WITH MINOR CONTAMINATION EXTENDING TO A DEPTH OF ABOUT 0.003-0.004in.

61-108-CL 250X

FIGURE 9. Ti-7Al-12Zr, S-3793, 0.062in. AS-ROUGH GROUND + 1650F (1/2 HR) AC WITH J-400 PROTECTIVE COATING + 1820F (1/2 HR) WQ IN SEALED COVERS. PROTECTION DURING AIR ANNEALING AT 1650F LIMITED DEPTH OF SURFACE CONTAMINATION TO 0.001-0.0015in.

could produce a differential polishing or etching behavior at the junction between the two areas and provide this line or zone of a different appearance.

Most of the protective coatings, which were used on samples air annealed at 1650F (1/2 hr) AC, offered little or no protection based on these metallographic studies. The coatings were essentially the same as those used in an earlier investigation on Ti-8Al-1Mo-1V (see Table 6 of the Eleventh Bimonthly Report)[3]; i.e., Turco 4367, Ti-Form II, Markal CRT-B, Dupont J-400, Al-Tex, and 3450-P (a cobalt-bearing ceramic). However, Markal CRT-B on Ti-5Al-5Sn-5Zr and Dupont J-400 on Ti-7Al-12Zr did minimize contamination. Little or no oxygen-rich layer was observed in the Ti-5Al-5Sn-5Zr coated with Markal CRT-B, while only a thin layer of contamination was present on Ti-7Al-12Zr coated with Dupont J-400 (Figure 9). Use of a protective coating of this type on Ti-7Al-12Zr could be of real advantage, as illustrated by the comparison of Figures 8 and 9.

All such coated samples were immersed in a Virgo descaling bath after annealing at 1650F (1/2 hr) AC and some of the coatings, including the J-400, were not adequately removed. In fact, the J-400 coating was retained as a white adherent layer. Perhaps other media are available to remove the coatings satisfactorily, but this area is one which would require more development; i.e., removal of coatings which offer adequate protection from oxygen contamination.

Although use of protective coatings on a surface-oxygen sensitive alloy, such as Ti-7Al-12Zr, appears attractive, it was felt that a refinement of this type would complicate the contract. This is especially true since removal of a minimum of 0.004in from gage is deemed necessary after annealing at 1650F to provide a uniform sheet surface condition. As a result, it appears that all of the annealing contamination would be removed during the subsequent finish grinding and pickling which are necessary operations just to obtain sheets in good physical shape and condition. Therefore, protective coatings will not be used for material in this contract.

On the basis of the studies described above and the creep-stability properties of fully mill processed sheets of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr (to be discussed in a later section), it is concluded that, to be safe, a minimum of 0.006-0.007in of metal should be removed from the gage of both alloys after finish rolling and prior to final annealing at 1650F (1/2 hr) AC. After final annealing, an additional 0.004-0.005in should be removed from the gage to provide contamination-free material with a good surface condition. Therefore, this cleaning schedule will be utilized on all sheets in the production phase of the contract.

Effect of Hydrogen on Creep-Stability and Notch Properties of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr Sheet

In a program similar to that described in an earlier section of this report for Ti-8Al-1Mo-1V, a laboratory investigation was conducted to determine the effect of hydrogen on the 1000F creep-stability and room-temperature notch tensile and notch rupture properties of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheet. These studies were performed on 0.062in sheets from the first two ingots, V-1540 and V-1541, which had been finish rolled from 1750 and 1800F, respectively, and mill annealed at 1350F (8 hrs).

As originally outlined, the tests were to be made covering the range of hydrogen contents of 40-250 ppm for Ti-5Al-5Sn-5Zr and 40-200 ppm for Ti-7Al-12Zr. At the outset, it was felt that of the two alloys, the latter might be more susceptible to the deleterious effects of hydrogen. Three heat treated conditions were to be studied for each composition: simulated mill annealed at 1350-1450F, alpha annealed at 1650F, and beta annealed at 1850F. All specimen blanks were vacuum outgassed at 1350F and then hydrogenated at 1350F to the desired levels in a modified Sievert's apparatus. After hydrogenation, those samples to be given a simulated mill annealing cycle or the long-time alpha anneal were sealed inside welded cover sheets of commercially pure titanium to prevent oxidation. Unfortunately, specimens of different hydrogen contents were sealed together in the same air-tight cover sheets and during the long-time annealing period, the hydrogen contents equalized such that all of the simulated mill annealed (1450F for 4 hrs) and 1650F (4 hrs) alpha annealed samples were at approximately the same hydrogen level. This situation, however, was not discovered until after these two groups of specimens had been tested and analyzed for hydrogen. The beta annealed samples were not sealed in cover sheets, but were annealed separately; consequently, the desired range of hydrogen contents was obtained for this condition.

At this point several specimens were repeated, but because of inferior specimen preparation techniques, results of the repeat tests are not considered reliable. In the repeat tests, only the currently-used mill annealing (1350F) and finish annealing cycles were studied; it should be noted that the 1350 and 1450F (4 hrs) cycles with slow heating and cooling used in the laboratory approximates an 8-hour annealing cycle utilized in production facilities on medium-size loads of sheets.

Results of the testing program are listed in Tables 11 and 12 for the two alloys. It can be seen that for the 1450F simulated mill annealed and 1650F (4 hrs) alpha annealed conditions, the hydrogen contents generally fell in the range of 95-120 ppm

TABLE 11. EFFECT OF HYDROGEN CONTENT ON THE 1000F CREEP-STABILITY AND ROOM-TEMPERATURE NOTCH TENSILE AND NOTCH-RUPTURE PROPERTIES OF Ti-5Al-5Sn-5Zr SHEET

(V-1540M, A-4801, 0.062in, longitudinal specimens; Finish rolled from 1750F and mill annealed at 1350F (8 hrs); Creep-stability exposure 1000F-25 Ksi-150 hrs)

Heat Treatment	H_2(1) ppm	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	H_2(2) ppm	NTS(3) Ksi	NR(4) Stress Ksi	NR(4) Time Hrs
Vacuum Annealed at 1350F +	85	Not Exp.	127.5	122	23	95	163	150	0.95
1450F (4 hrs) FC to 1000F(7)	107	0.26	131	120	20(5)	-	161	-	-
	-	0.17	130	122	15(6)	-	-	-	-
1450F (4 hrs) FC to 1000F(7)	-	Not Exp.	127.5	121.5	22.5	99	159	150	0.58
	111	0.22	131	120	21(5)	-	163	-	-
	-	0.19	130	119	24(6)	-	-	-	-
Hydrogenated at 1350F +	-	Not Exp.	128	123	22	110	-	150	0.37
1450F (4 hrs) FC to 1000F(7)	100	0.23	131	123	20(5)	-	159	-	-
	-	0.26	130	119	20(6)	-	-	-	-
Hydrogenated at 1350F +	-	Not Exp.	126.5	121.5	24.5	100	158	Faulty	test
1450F (4 hrs) FC to 1000F(7)	103	0.22	127	120	8(6)	-	159	-	-
Hydrogenated at 1350F +	89	Not Exp.	128	121.5	22	109	165	150	0.25
1450F (4 hrs) FC (7)	106	0.20	130	121	19(5)	-	162	-	-
	-	0.23	129	119	22(6)	-	-	-	-
Hydrogenated at 1350F +	204	Not Exp.	134.1	127.8	21	-	173	160	0.13
1350F (4 hrs) FC to 1000F(8)	198	0.32	-	-	(5,8)	-	-	-	-
Hydrogenated at 1350F +	247	Not Exp.	133.6	125.0	20	-	175	160	0.17
1350F (4 hrs) FC to 1000F(8)	232	0.27	134.1	121.6	19(5)	-	-	-	-

(Continued)

TABLE 11. (Continued)

Heat Treatment	H_2(1) ppm	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	H_2(2) ppm	NTS(3) Ksi	NR(4) Stress Ksi	NR(4) Time Hrs
Vacuum Annealed at 1350F + 1650F (4 hrs) AC (7)	111	Not Exp.	123	114.5	22	101	154	150	0.03
	100	0.039	124	114	20(5)	-	153	-	-
	-	0.014	124	117	21(6)	-	-	-	-
1650F (4 hrs) AC(7)	-	Not Exp.	122.5	114	20.5	98	160	140	3.58
	95	0.12	125	114	19(5)	-	158	-	-
	-		129	117	23(6)	-	-	-	-
Hydrogenated at 1350F + 1650F (4 hrs) AC (7)	-	Not Exp.	122	113	21.5	84	157	140	3.37
	99	0.038	124	116	20(5)	-	157	-	-
	-	0.042	128	120	22(6)	-	-	-	-
Hydrogenated at 1350F + 1650F (4 hrs) AC (7)	-	Not Exp.	123	114	22	87	154	140	5.00
	119	0.062	126	117	21(5)	-	158	-	-
	-	0.019	129	119	23(6)	-	-	-	-
Hydrogenated at 1350F + 1650F (4 hrs) AC (7)	139	Not Exp.	122.5	114	20.5	83	159	150	0.03
	103	0.089	126	117	20(5)	-	161	-	-
	-	0.032	123	112	23(6)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F + 1650F (1/2 hr) AC (8)	198	Not Exp.	131.8	112.9	20	-	169	150	2.50
	183	0.090	-	-	(5,8)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F + 1650F (1/2 hr) AC (8)	251	Not Exp.	132.4	110.8	20	-	168	150	0.92
	225	0.094	-	-	(5,8)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F + 1750F (15 min) AC (8)	198	Not Exp.	131.3	108.9	14	-	168	150	1.00
	199	0.22	-	-	(5,8)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F + 1750F (15 min) AC (8)	270	Not Exp.	132.5	105.7	11	-	168	150	0.10
	242	0.27	-	-	(5,8)	-	-	-	-

(Continued)

TABLE 11. (Continued)

Heat Treatment	H_2 (1) ppm	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	H_2 (2) ppm	NTS (3) Ksi	NR (4) Stress Ksi	NR (4) Time Hrs
Vacuum Annealed at 1350F +	53	Not Exp.	126.5	107.5	16	37	152	130	3.00
1850F (10 min) AC (7)	29	0.074	129	118	13(5)	-	145	-	-
	-	0.086	129	124	17(6)	-	-	-	-
1850F (10 min) AC (7)	-	Not Exp.	127.5	110	15.5	54	155	140	5.00
	38	0.095	130	118	8(5)	-	149	-	-
	-	0.065	129	118	17(6)	-	-	-	-
Hydrogenated at 1350F +	-	Not Exp.	132	110.5	18.5	156	160	140	0.38
1850F (10 min) AC (7)	125	0.051	136	126	5(5)	-	158	-	-
	-	0.065	135	125	15(6)	-	-	-	-
Hydrogenated at 1350F +	-	Not Exp.	133	110	19.5	215	158	140	0.15
1850F (10 min) AC (7)	188	0.10	137	127	3(5)	-	160	-	-
	-	0.079	139	123	19(6)	-	-	-	-
Hydrogenated at 1350F +	213	Not Exp.	134	107.5	20	217	151	140	1.80
1850F (10 min) AC (7)	206	0.073	136	129	2(5)	-	158	-	-
	-	0.062	139	125	18(6)	-	-	-	-

(1) Hydrogen analysis of indicated individual tensile and/or creep-stability specimen.
(2) Hydrogen analysis of indicated individual notch rupture specimen.
(3) Notch tensile strength; 0.5in gage width, 0.25in notch width, 0.010in notch radius, and $K_t = 4.2$.
(4) Notch rupture test using same specimen configuration as (3); failed at time and stress level indicated except for those listed as 5.00 hours. In these instances, the specimen withstood 5 hours at stress noted. All other specimens satisfactorily passed 10 Ksi lower stress prior to loading and failing in less than 5 hours.
(5) Tensile tested at room temperature after creep exposure without surface pickling or conditioning.

(Continued)

TABLE 11. (Continued)

(6) Acid pickled 0.003in from gage after creep exposure but prior to tensile testing at room temperature.

(7) Anodically pickled 0.002-0.003in after heat treatment and machining to a high surface polish; no indication of machine tool marks or contamination.

(8) Acid pickled after heat treatment but before machining. Test results and visual examination of specimens showed that machine tool marks on milled edges developed shallow cracks and that some surface contamination remained on a few of the samples such that the results are questionable.

TABLE 12. **EFFECT OF HYDROGEN CONTENT ON THE 1000F CREEP-STABILITY AND ROOM-TEMPERATURE NOTCH TENSILE PROPERTIES OF Ti-7Al-12Zr SHEET**

(V-1541M, A-4799, 0.062in, longitudinal specimens; Finish rolled from 1800F and mill annealed at 1350F (8 hrs); Creep-stability exposure 1000F-25 Ksi-150 hrs)

Heat Treatment	H_2 (1) ppm	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	H_2 (2) ppm	NTS (3) Ksi	NR (4) Stress Ksi	NR (4) Time Hrs
Hydrogenated at 1350F + 1450F (4 hrs) FC to 1000F(7)	-	Not Exp.	145.5	138.3	23	-	-	-	-
	57	0.19	145.5	131.8	20(5)	-	-	-	-
	72	0.19	145.2	133.1	11(6)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs)FC to 1000F(8)	77	Not Exp.	145.6	132.2	10(9)	-	175.1	170	0.02
	75	0.21	-	-	(5,9)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F(8)	156	Not Exp.	149.7	135.5	20	-	189.5	180	0.25
	155	0.19	-	-	(5,9)				
Hydrogenated at 1350F + 1650F (4 hrs) AC (7)	137	Not Exp.	137.4	128.4	23.5	-	173.1	160	4.75
	86	0.083	141.0	125.9	15(5)	75	174.7	-	-
	83	0.052	141.0	129.3	15(6)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F + 1650F (1/2 hr) AC (8)	85	Not Exp	141.5	124.2	16	-	178.7	170	0.08
	75	0.018	-	-	(5,9)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F + 1650F (1/2 hr) AC (8)	167	Not Exp.	145.7	131.1	19	-	185.5	170	2.67
	156	0.043	-	-	(5,9)	-	-	-	-
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F + 1750F (15 min) AC (8)	102	Not Exp.	137.5	122.7	7(9)	-	162.2	160	0.00
	87	0.036	-	-	(5,9)	-	-	-	-

(Continued)

TABLE 12. (Continued)

Heat Treatment	H_2 (1) ppm	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	H_2 (2) ppm	NTS (3) Ksi	NR (4) Stress Ksi	NR (4) Time Hrs
Hydrogenated at 1350F + 1350F (4 hrs) FC to 1000F + 1750F (15 min) AC (8)	173	Not Exp.	142.2	126.1	(9)	-	172.1	150	1.33
	159	0.051	-	-	(5,9)	-	-	-	-
Hydrogenated at 1350F + 1850F (10 min) AC (7)	-	Not Exp.	150.7	130.4	14	-	171.9	170	0.02
	123	0.052	118.1	Broke before YS	0(5)	122	175.7	-	-
	138	0.094	148.5	143.6	2(6)	-	-	-	-

(1) Hydrogen analysis of indicated individual tensile and/or creep-stability specimen.
(2) Hydrogen analysis of indicated individual notch tensile specimen.
(3) Notch tensile strength; 0.5in gage width, 0.25in notch width, 0.010in notch radius, and $K_t = 4.2$.
(4) Broke at end of gage length.
(5) Tensile tested at room temperature after creep exposure without surface pickling or conditioning.
(6) Acid pickled 0.003in from gage after creep exposure but prior to tensile testing at room temperature.
(7) Anodically pickled 0.002-0.003in after heat treatment and machining to a high surface polish; no indication of machine tool marks on milled edges or residual surface contamination.
(8) Acid pickled after heat treatment but before specimen machining. Test results and visual examination of specimens showed that machine tool marks on milled edges developed shallow cracks and that surface contamination remained on several samples.
(9) Evidence of cracks on milled edges and some surface contamination, such that the results are questionable.

for Ti-5Al-5Sn-5Zr and 60-90 ppm for Ti-7Al-12Zr. Higher hydrogen levels were obtained on beta annealed samples and on the repeat specimens which were given a simulated mill annealing cycle at 1350F, with and without subsequent annealing at 1650F (1/2 hr) AC or 1750F (15 min) AC. However, the data from these repeat creep-stability specimens are, for the most part, considered invalid because of machine tool marks on the edges of most of the samples and residual surface contamination which was not thoroughly removed after the final heat treatments in air.

Reviewing the results in Table 11, it is seen that no instability was encountered in Ti-5Al-5Sn-5Zr sheet as mill annealed at 1450F or finish annealed at 1650F (4 hrs) AC at hydrogen contents up to about 120 ppm, the highest level for which reliable results were obtained in these two conditions. At the higher hydrogen contents of 200-250 ppm, no embrittlement was observed after creep exposure even though specimen preparation procedures were sub-standard for the repeat tests. Good notch tensile and notch rupture strengths (5-hour sustained loads) were also provided, even at the higher hydrogen levels. Unfortunately, hydrogen values less than 200 ppm were not evaluated for the alpha-beta annealing treatment, 1750F (15 min) AC, but at these higher levels no embrittlement was encountered in spite of the contaminated surfaces.

Except for one test of 1850F beta annealed Ti-5Al-5Sn-5Zr at 29 ppm hydrogen, rather serious surface instability was obtained in the high-temperature annealed material. In fact, the difference in surface stability between 29 and 38 ppm hydrogen was quite pronounced, indicating that the beta annealed sheet has a very low tolerance for hydrogen. This observation also was previously made on beta duplex annealed Ti-8Al-1Mo-1V in an earlier section. However, in both alloys, acid pickling after creep exposure restored the original ductility, showing that no metallurgical instability is manifest at hydrogen levels up to 200 ppm in Ti-5Al-5Sn-5Zr sheet. After creep exposure, the yield strength of beta annealed Ti-5Al-5Sn-5Zr increased markedly and, as beta annealed, good notch tensile strengths were produced, although some deterioration of notch rupture properties was indicated, particularly as the hydrogen content was increased from 54 to 156 ppm and higher. No consistent trend of creep resistance with variations in hydrogen was evident, although it was obvious that alpha annealing at 1650F and beta annealing at 1850F provided much better creep resistance than mill annealing at 1350 or 1450F and alpha-beta annealing at 1750F.

Considering the results in Table 12 for Ti-7Al-12Zr, it is seen that little instability was encountered in 1450F mill

annealed specimens at hydrogen contents of 57-72 ppm, although the data are very limited for this condition. Some loss in ductility after 1000F creep exposure was observed for 1650F (4 hrs) AC annealed samples at about 85 ppm, but certainly there was no embrittlement. Severe instability was evident after beta annealing at 1850F with a hydrogen level of 123-138 ppm, and although the data are quite limited, Ti-7Al-12Zr in this condition appears to have a very low tolerance for hydrogen, both from the standpoint of surface embrittlement as well as metallurgical instability. No conclusions can be made from the results of the repeat tests, since surface contamination and machine tool marks on the edges masked any measure of the effect of hydrogen on creep-stability properties. Good notch tensile and notch rupture properties were obtained throughout, although the lower strengths were exhibited by samples which were alpha-beta or beta annealed. A decrease in notch-rupture strength was indicated for alpha-beta annealed specimens as the hydrogen increased from approximately 100 ppm to 160-170 ppm. Greater creep deformation values were obtained in the 1350 and 1450F mill annealed conditions compared to the higher-temperature annealing treatments. The best creep resistance was indicated for an alpha annealed (1650F - 1/2 hr) specimen with the lowest hydrogen content (75 ppm), but the data are far too limited to conclude whether hydrogen in this range has an effect on creep resistance.

To supplement this investigation, which could have provided more information on the effect of a greater range of hydrogen levels, one 0.020in fully-processed sheet of each alloy was given thermal- and creep-stability tests at 800-1000F in both the alpha (1650F) and alpha-beta annealed (1750F) conditions. This material was selected because it contained abnormally high hydrogen contents. These two sheets were procured from the same groups of materials as Panels S-3793 (Ti-5Al-5Sn-5Zr) and S-3795 (Ti-7Al-12Zr), which were described in the preceding section (Table 8). However, after these panels were sheared for evaluation, the material was then final annealed at 1650F (1/2 hr) AC, finish ground, and pickled. Thus, for a study of the 1650F annealed condition, the fully-processed as-received material was used, while for the alpha-beta annealed conditions, these treatments were superimposed on samples in a laboratory operation.

Results of this supplemental investigation are listed in Tables 13 and 14 for Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, respectively, showing that no stability problem was encountered in 1650F (1/2 hr) AC annealed Ti-5Al-5Sn-5Zr even at these higher hydrogen levels of 220-260 ppm. However, in the 1750F alpha-

TABLE 13. THERMAL AND CREEP-STABILITY OF MILL PROCESSED HIGH HYDROGEN Ti-5Al-5Sn-5Zr SHEET
(V-1540B, A-6751 Sheet No. 3, 0.020in longitudinal specimens; Finish rolled from 1750F and finish annealed at 1650F (1/2 hr) AC)

Stability Exposure	O_2 %	H_2 ppm	Dir	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
None			L	-	129.0	111.7	17.5*
"			T	-	125.1	111.4	18.5*
"			L	-	127.2	112.3	23.0
800F - 150 Hrs			L	-	125.3	123.7	19.0
" "			L	-	122.0	120.2	25.0(1)
800F-65 Ksi-150Hrs	0.093	220	L	0.43	132.4	132.4	19.0
" " "			L	0.26	132.4	130.8	22.0
900F - 150 Hrs			L	-	127.7	121.3	14.5
" "			L	-	122.7	115.2	20.0(1)
900F-45Ksi-150Hrs			L	0.029	131.8	125.9	21.0
" " "			L	0.036	130.3	127.1	19.5
1000F - 150 Hrs			L	-	129.9	126.7	17.5
" "			L	-	125.7	118.5	16.0(1)
1000F-25.5Ksi-150Hrs	0.085	261	L	0.065	131.5	127.2	19.0
1000F-23.4Ksi-150Hrs			L	0.000	129.6	126.4	20.0
<u>1750F (10 min) AC</u>							
None			L	-	125.8	108.2	19.0
1000F - 150 Hrs			L	-	127.9	122.0	9.5(2)
" "			L	-	124.1	115.2	17.0(1)
1000F-25Ksi-150Hrs	0.064	200	L	0.090	128.7	122.8	9.0
" " "			L	0.094	131.3	122.2	7.0(1)
<u>1750F (10 min) AC + 1300F (8 hrs)</u>							
None			L	-	127.0	117.4	19.0
1000F - 150 Hrs			L	-	129.1	124.7	9.0(2)
" "			L	-	113.7	103.7	15.0(1)
1000F-25Ksi-150Hrs			L	(3)	(3)	(3)	(3)
" " "			L	4.69	134.6	105.8	10.0

* Elongation measured in standard 2in gage length specimen.
(1) Acid pickled 0.003in from gage after exposure; all others tensile tested as exposed with no surface conditioning.
(2) Broke at end of gage length.
(3) Broke on loading during creep-stability exposure.

TABLE 14. THERMAL AND CREEP-STABILITY OF MILL PROCESSED HIGH HYDROGEN Ti-7Al-12Zr SHEET (V-1541B, A-6576 Sheet No. 5, 0.020in longitudinal specimens; Finish rolled from 1750F and finish annealed at 1650F (1/2 hr) AC).

Stability Exposure	O_2 %	H_2 ppm	Dir	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (in) %
None			L	-	141.7	129.8	15.5*
"			T	-	139.9	129.6	13.5*
"			L	-	135.8	123.2	16.5
800F - 150 Hrs			L	-	134.6	133.2	3.5
" "			L	-	136.8	135.2	17.0(1)
800F-65 Ksi-150 Hrs	0.100	61	L	0.01	133.9	132.6	4.0(2)
" " "			L	0.00	145.2	140.7	13.0(1)
900F - 150 Hrs			L	-	130.5	Broke before YS	(2)
" "			L	-	131.7	"	(1,2)
1000F - 150 Hrs			L	-	Broke	before YS	(2)
" "			L	-	136.7	135.5	2.0(1)
1000F-25 Ksi-150 Hrs	0.097	127	L	0.036	141.9	132.5	3.5
" " "			L	0.040	130.5	128.5	1.0(1,2)
<u>1750F (10 min) AC</u>							
1000F - 150 Hrs			L	-	132.4	Broke before YS	(2)
" "			L	-	132.7	130.5	3.0(1,2)
1000F-25 Ksi-150 Hrs	0.074	95	L	0.087	129.7	128.0	1.0
" " "			L	0.090	128.1	122.1	2.0(1)
<u>1750F (10 min) AC + 1300F (8 hrs)</u>							
1000F - 150 Hrs			L	-	Broke	before YS	(2)
" "			L	-	"	" "	(1,2)
1000F-25 Ksi-150 Hrs			L	0.14	128.4	Broke at YS	(2)
" " "			L	0.16	139.5	136.0	1.0(1,2)

* Elongation measured in standard 2in gage length specimen.

(1) Acid pickled 0.003in from gage after exposure; all others tensile tested as exposed with no surface conditioning.

(2) Broke at end of gage length.

beta annealed samples, some surface instability was exhibited during 1000F unstressed exposures and possibly some metallurgical instability under stress, also, with a hydrogen content of about 200 ppm. Although reasons for it are not readily apparent, the difference in creep deformation between the 1750F (10 min) AC and 1750F (10 min) AC + 1300F (8 hrs) treatments was phenomenal. In fact, one of the latter treated specimens fractured on loading to 25 Ksi at 1000F.

In contrast to the excellent stability provided by the high hydrogen Ti-5Al-5Sn-5Zr sheet (Table 13), the higher hydrogen and/or oxygen Ti-7Al-12Zr material in Table 14 exhibited very poor stability. As annealed at 1650F (1/2 hr) AC, much of the instability at 800F was of the surface variety; i.e., most of the ductility was restored by acid pickling the exposed samples. However, at 900 and 1000F, serious embrittlement was observed even after acid pickling in both the alpha and alpha-beta annealed conditions. It should be emphasized, however, that after post-exposure acid pickling, the samples were often only 0.010-0.012in thick (particularly the ones laboratory annealed at 1750F) and, consequently, were very difficult to tensile test in a normal fashion. Although the creep deformation of the specimens alpha-beta annealed at 1750F (10 min) AC + 1300F (8 hrs) was higher than for those given the simple anneal of 1750F (10 min) AC, the difference between the two conditions in Ti-7Al-12Zr was small compared to the drastic difference between these two anneals in Ti-5Al-5Sn-5Zr (see Table 13).

This overall investigation did show that good stability was achieved in alpha annealed Ti-5Al-5Sn-5Zr sheet at hydrogen contents up to 200-250 ppm and, therefore, it is concluded that 150 ppm is a completely safe hydrogen level in Ti-5Al-5Sn-5Zr annealed at 1650F. This level of hydrogen is being recommended for incorporation in the automatic release property specifications for the alloy.

Conclusions regarding the hydrogen tolerance in Ti-7Al-12Zr are not as readily drawn because of the limited data available, but with only a moderate loss in ductility of low oxygen sheet at 86 ppm and little instability indicated at 57-72 ppm (Table 12), it is concluded tentatively that 100 ppm hydrogen is an acceptable hydrogen content. This level is being recommended as part of the automatic release property specification for Ti-7Al-12Zr sheet.

Effects of Annealing Time and Subsequent Cooling Rate on Tensile and Stability Properties of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr Sheet

This investigation was undertaken to determine the effects of annealing time at 1650F and subsequent cooling rate on the tensile, creep, and stability properties of the six panels used for the process contamination studies described in the previous section. These panels were selected because they represented material mill processed to the stage of finish annealing, and laboratory evaluation, therefore, would indicate the nature of the final product properties. Also of interest was the effect of cooling rate after annealing on creep and stability, since maintaining the hydrogen level at a maximum of 100 ppm in Ti-7Al-12Zr might require that thin gage material be vacuum annealed as the final thermal cycle. If so, such an annealing treatment would, of necessity, be accompanied by a slow cooling rate from 1650F.

Longitudinal samples were cut from each of the six mill annealed-and-ground panels (S-3790 through S-3796), acid pickled nominally 0.008in from gage to insure contamination-free surfaces, and annealed inside welded-and-sealed cover sheets of commercially pure titanium at 1650F (1/2 hr) AC, 1650F (2 hrs) AC, and 1650F (2 hrs) FC to 1000F, with the latter being programed through heating and cooling such that the cycle simulated that used in vacuum annealing. Following the annealing treatments, the samples were cleaned by acid pickling 0.002in from gage, machined, and tested with both stressed and unstressed specimens exposed at 800-1000F for 150 hours.

Results of standard 2in gage length tensile tests are presented for both alloys in Table 15 while the stability properties for the three panels of Ti-5Al-5Sn-5Zr are listed in Table 16 and stability data on the three panels of Ti-7Al-12Zr are shown in Table 17. The major item of interest in Table 15 is the slight increase in strength achieved in both alloys with the annealing treatment, 1650F (2 hrs) FC to 1000F, particularly the yield strength which appeared to increase somewhat more in Ti-7Al-12Zr than in Ti-5Al-5Sn-5Zr. This observation indicates again that some reaction is occurring in the lower temperature range, 1000-1300F, the region through which the specimens passed during the slow cooling cycle. In Ti-5Al-5Sn-5Zr this cycle actually enhanced the tensile elongation slightly, but in Ti-7Al-12Zr the ductility decreased appreciably, particularly in the two lighter gage panels (S-3795 and S-3793). Therefore, on the basis of room-temperature tensile properties, a vacuum annealing or slow heating-slow cooling cycle at 1650F appears to be quite satisfactory for Ti-5Al-5Sn-5Zr, but is not recommended for Ti-7Al-12Zr.

TABLE 15. <u>EFFECTS OF ANNEALING TIME AND COOLING RATE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF Ti-5Al-5Sn-5Zr AND Ti-7Al-12Zr SHEETS</u>
(Finish rolled from 1750F, mill annealed at 1350F (8 hrs), ground, acid pickled 0.008in from gage, and annealed as shown; averages of duplicate tests)

Sheet No.	Gage in	Heat Treatment	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %
Ti-5Al-5Sn-5Zr (V-1540)						
S-3792	0.020	1650F (1/2 hr) AC	L	121.8	109.4	16.0
		" "	T	120.1	111.0	13.5
		1650F (2 hrs) AC	L	122.1	112.6	15.5
		" "	T	120.0	110.1	15.0
		1650F (2 hrs) FC to 1000F	L	123.7	115.8	17.3
		" " "	T	121.0	114.9	16.3
S-3790	0.062	1650F (1/2 hr) AC	L	118.9	110.2	15.5
		" "	T	118.7	111.9	16.8
		1650F (2 hrs) AC	L	117.0	108.9	16.3
		" "	T	117.5	110.0	17.0
		1650F (2 hrs) FC to 1000F	L	118.4	113.2	20.3
		" " "	T	120.2	115.1	18.5
S-3796	0.090	1650F (1/2 hr) AC	L	120.3	110.3	18.3
		" "	T	120.5	111.0	16.3
		1650F (2 hrs) AC	L	119.5	110.2	19.0
		" "	T	119.7	110.5	17.0
		1650F (2 hrs) FC to 1000F	L	119.3	112.2	19.0
		" " "	T	120.5	113.5	17.8
Ti-7Al-12Zr (V-1541)						
S-3795	0.020	1650F (1/2 hr) AC	L	137.5	125.9	13.3
		" "	T	132.5	126.3	9.0
		1650F (2 hrs) AC	L	137.4	125.1	13.5
		" "	T	135.4	125.0	13.8
		1650F (2 hrs) FC to 1000F	L	139.2	126.8	10.0
		" " "	T	136.6	128.7	5.8
S-3793	0.062	1650F (1/2 hr) AC	L	133.0	122.4	16.5
		" "	T	135.0	123.6	14.5
		1650F (2 hrs) AC	L	-	-	-
		" "	T	133.7	122.0	16.3
		1650F (2 hrs) FC to 1000F	L	136.6	126.5	11.0
		" " "	T	138.7	128.5	8.0

(Continued)

TABLE 15. (Continued)

Sheet No.	Gage in	Heat Treatment	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %
S-3791	0.090	1650F (1/2 hr) AC	L	132.3	122.5	16.5
		" "	T	135.6	125.2	15.0
		1650F (2 hrs) AC	L	131.7	120.3	16.5
		" "	T	133.5	123.1	17.0
		1650F (2 hrs) FC to 1000F	L	135.0	125.9	15.8
		" " "	T	137.5	128.7	13.5

TABLE 16. EFFECTS OF ANNEALING TIME AND COOLING RATE ON THE TENSILE AND STABILITY PROPERTIES OF Ti-5Al-5Sn-5Zr SHEETS
(V-1540 finish rolled from 1750F, mill annealed at 1350F (8 hrs), ground, laboratory acid pickled 0.008in from gage, and annealed as indicated; longitudinal specimens)

Sheet No.	Gage in	Heat Treatment	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
S-3792	0.020	1650F (1/2 hr) AC	None	-	118.7	108.2	18.0
			800F - 150 Hrs	-	120.4	119.2	24.0
(5.12% Al, 5.02% Sn, 4.49% Zr*			800F-60 Ksi-150 Hrs	0.010	116.5	113.6	15.0
0.087% O_2, 156 ppm H_2)			" " "	0.032	124.3	122.7	19.0(1)
			900F - 150 Hrs	-	124.1	117.3	19.0
	(0.070% O_2, 65 ppm H_2)		900F-55 Ksi-150 Hrs	0.065	119.5	114.7	21.0
Beta Transus	1800-1820F		" " "	0.98(3)	127.0	123.8	19.0
			1000F - 150 Hrs	-	123.4	115.4	16.0
			" "	-	124.1	116.5	20.0(1)
			1000F-25 Ksi-150 Hrs	0.038	-	-	13.0(2)
			" " "	0.021	115.9	112.2	14.5(1,2)
		1650F (2 hrs) AC	None	-	118.6	109.7	14.0
			800F - 150 Hrs	-	114.3	111.4	18.0
			800F-60 Ksi-150 Hrs	0.032	115.5	111.8	18.0
			" " "	0.040	127.2	124.5	20.5
			900F - 150 Hrs	-	120.6	116.6	19.0
	(0.090% O_2, 66 ppm H_2)		900F-55 Ksi-150 Hrs	0.032	116.6	111.4	19.0
			1000F - 150 Hrs	-	123.4	114.6	17.0
			" "	-	117.5	112.0	15.0(1)
			1000F-25 Ksi-150 Hrs	0.031	121.9	108.1	20.0
			" " "	0.016	101.7	100.0	4.0(1,4)
		1650F (2 hrs) FC to 1000F	None	-	123.2	120.2	20.0
			800F - 150 Hrs	-	121.5	118.9	19.0
			800F-61 Ksi-150 Hrs	0.31	115.3	113.8	18.0
			800F-60 Ksi-150 Hrs	0.087	124.7	123.5	22.0
			900F - 150 Hrs	-	123.5	110.1	13.0
	(0.084% O_2, 110 ppm H_2)		900F-55 Ksi-150 Hrs	0.09	117.8	110.6	20.0
			" " "	0.13	123.8	118.3	12.0

(Continued)

TABLE 16. (Continued)

Sheet No.	Gage in	Heat Treatment	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
			1000F - 150 Hrs	-	121.2	113.5	23.0
			" "	-	118.3	113.2	12.0(1)
			1000F-25 Ksi-150 Hrs	0.066	120.8	113.2	13.0(2)
			" " "	0.074	90.2	88.2	2.0(1,4)
			" " "	0.072	122.0	112.6	14.0
S-3790	0.062	1650F (1/2 hr) AC	None	-	120.0	110.1	23.0
			800F - 150 Hrs	-	120.0	116.0	25.5
(5.13% Al, 5.03% Sn, 4.53% Zr*, 0.07% O_2, 88 ppm H_2)			800F-65 Ksi-150 Hrs	0.56	122.0	115.8	22.0
			" " "	0.69	122.0	122.0	27.0(1)
			900F - 150 Hrs	-	122.7	117.2	23.0
		(0.063% O_2, 42 ppm H_2)	900F-45 Ksi-150 Hrs	0.00	120.6	116.1	18.0
			" " "	0.00	119.2	114.8	15.0(1)
			1000F - 150 Hrs	-	123.2	116.2	21.5
Beta Transus <1800F			" "	-	122.0	114.8	23.0(1)
			1000F-25 Ksi-150 Hrs	0.018	122.0	115.8	22.0
			" " "	0.022	120.2	113.2	21.0(1)
		1650F (2 hrs) AC	None	-	117.9	108.8	23.0
			800F - 150 Hrs	-	117.4	113.2	27.0
			800F-65 Ksi-150 Hrs	1.25	126.0	123.8	24.0
			" " "	0.99	121.8	121.8	18.0(1,2)
			900F - 150 Hrs	-	119.8	115.5	22.0
		(0.064% O_2, 46 ppm H_2)	900F-45 Ksi-150 Hrs	0.00	119.6	115.1	24.0
			" " "	0.00	117.9	112.2	27.0(1)
			1000F - 150 Hrs	-	121.1	115.2	18.0
			" "	-	117.8	111.0	21.0(1)
			1000F-25 Ksi-150 Hrs	0.012	118.7	112.1	18.0
			" " "	0.018	118.5	111.8	23.0(1)
		1650F (2 hrs) FC to 1000F	None	-	121.0	116.7	27.0
			800F - 150 Hrs	-	120.8	116.6	20.0
			800F-65 Ksi-150 Hrs	1.04	124.6	119.1	15.0
			" " "	1.26	125.5	124.6	16.0(1)

(Continued)

TABLE 16. (Continued)

Sheet No.	Gage in	Heat Treatment	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
			900F - 150 Hrs	-	122.7	118.4	23.0
	(0.061% O_2, 95 ppm H_2)		900F-45 Ksi-150 Hrs	0.063	123.4	117.1	25.5
			" " "	0.00	120.1	112.9	22.0(1)
			1000F - 150 Hrs	-	119.8	114.2	19.0
			" "	-	122.4	117.3	25.0(1)
			1000F-25 Ksi-150 Hrs	0.058	122.2	116.4	13.0
			" " "	0.088	110.6	109.6	3.5(1,2,5)
S-3796	0.090	1650F (1/2 hr) AC	None	-	119.5	109.9	21.0
			800F - 150 Hrs	-	119.8	114.0	24.0
(5.10% Al, 4.59% Sn, 4.98% Zr*, 0.07% O_2, 67 ppm H_2)			800F-60 Ksi-150 Hrs	0.16	119.0	117.2	22.0
			" " "	0.14	118.2	116.4	23.0
			900F - 150 Hrs	-	121.9	116.1	19.5
	(0.067% O_2, 40 ppm H_2)		900F-55 Ksi-150 Hrs	0.16	120.3	115.4	20.0
			" " "	0.083	120.9	112.0	14.0(2)
Beta Transus <1800F			1000F - 150 Hrs	-	123.3	115.7	19.5
			" "	-	121.5	113.5	21.0(1)
			1000F-25 Ksi-150 Hrs	0.00	121.7	115.1	20.0
			" " "	0.024	120.4	110.8	21.0(1)
		1650F (2 hrs) AC	None	-	118.3	108.3	20.0
			800F - 150 Hrs	-	118.3	112.8	23.0
			800F-60 Ksi-150 Hrs	0.22	120.0	119.2	24.0
			" " "	0.25	116.8	114.7	23.0
			900F - 150 Hrs	-	120.4	113.9	23.0
	(0.062% O_2, 45 ppm H_2)		900F-55 Ksi-150 Hrs	1.33(3)	121.0	120.1	20.0
			" " "	0.069	118.0	113.9	16.0
			1000F - 150 Hrs	-	120.7	112.6	20.0
			" "	-	118.8	116.3	21.0(1)
			1000F-25 Ksi-150 Hrs	0.009	121.0	113.4	20.0
			" " "	0.006	117.6	108.8	18.0(1)

(Continued)

TABLE 16. (Continued)

Sheet No.	Gage in	Heat Treatment	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
		1650F (2 hrs) FC to 1000F	None	-	121.6	113.0	24.0
			800F - 150 Hrs	-	122.4	115.7	20.0
			900F - 150 Hrs	-	121.4	114.3	23.0
			1000F - 150 Hrs	-	121.2	115.2	24.0
			" "	-	121.6	113.2	20.0(1)
		(0.074% O_2, 77 ppm H_2)	1000F-25 Ksi-150 Hrs	0.077	121.6	114.6	6.0
			" " "	0.066	127.8	118.5	18.0(1)

* Zirconium analyses performed before refinements made in analytical technique (3); values estimated to be approximately 10 percent low.

(1) Acid pickled 0.003in from gage after stability exposure but prior to tensile testing; all others tensile tested as-exposed without surface conditioning or pickling.

(2) Broke at end of gage length.

(3) Creep deformation obviously high due to error in loading or in deformation measurement.

(4) Specimen pitted and too thin to obtain satisfactory test results.

(5) Evidence of stress corrosion in fracture.

TABLE 17. **EFFECTS OF ANNEALING TIME AND COOLING RATE ON THE TENSILE AND STABILITY PROPERTIES OF Ti-7Al-12Zr SHEETS** (V-1541 finish rolled from 1750F, mill annealed at 1350F (8 hrs), ground, laboratory acid pickled 0.008in from gage, and annealed as indicated; longitudinal specimens)

Sheet No.	Gage in	Heat Treatment	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
S-3795	0.020	1650F (1/2 hr) AC	None	-	133.2	126.2	14.5
			800F - 150 Hrs	-	135.3	132.6	15.0
(6.80% Al, 10.87% Zr*,			800F-76 Ksi-150 Hrs	0.065	134.5	134.5	9.0
0.12% O_2, 38 ppm H_2)			800F-65 Ksi-150 Hrs	0.003	138.0	135.3	14.0(1)
			900F - 150 Hrs	-	141.3	136.8	12.0
	(0.088% O_2, 56 ppm H_2)		900F-55 Ksi-150 Hrs	0.029	135.1	130.9	4.5(2)
			" " "	0.054	134.1	131.4	1.0(1)
Beta Transus 1800-1820F			1000F - 150 Hrs	-	141.4	128.7	10.0
			" "	-	143.1	134.4	11.0(1)
			1000F-25 Ksi-150 Hrs	0.034	96.0	Broke	before YS
			" " "	0.047	71.4	67.3	1.5(1,3)
		1650F (2 hrs) AC	None	-	132.8	122.1	18.0
			800F - 150 Hrs	-	127.9	125.6	5.5(2)
			900F - 150 Hrs	-	138.8	130.8	3.0
			1000F - 150 Hrs	-	124.6	120.3	2.0(2)
			" "	-	89.7	Broke	before YS(1)
	(0.13% O_2, 70 ppm H_2)		1000F-25 Ksi-150 Hrs	0.030	128.0	121.2	2.0
			" " "	0.051	61.8	Broke	before YS(1,3)
		1650F (2 hrs) FC to 1000F	None	-	142.0	131.8	9.0
			800F - 150 Hrs	-	141.8	131.0	8.0(2)
			900F - 150 Hrs	-	136.0	129.4	9.0
			1000F - 150 Hrs	-	137.3	125.6	4.0
			" "	-	136.9	125.2	11.0(1)
	(0.11% O_2, 141 ppm H_2)		1000F-25 Ksi-150 Hrs	0.083	135.9	131.7	(2)
			" " "	0.085	104.4	Broke	before YS(1)

(Continued)

TABLE 17. (Continued)

Sheet No.	Gage in	Heat Treatment	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
S-3793	0.062	1650F (1/2 hr) AC	None	-	132.1	120.6	17.5
			800F - 150 Hrs	-	135.1	129.2	12.0
(6.78% Al, 11.15% Zr*,			800F-65 Ksi-150 Hrs	0.012	132.7	125.6	12.0
0.09% O_2, 68 ppm H_2)			" " "	0.000	141.2	131.8	5.0(1,3)
			900F - 150 Hrs	-	141.2	132.7	6.5
	(0.061% O_2, 41 ppm H_2)		900F-45 Ksi-150 Hrs	0.000	138.1	128.6	4.5
			" " "	0.000	126.4	125.1	1.0(1,3)
			1000F - 150 Hrs	-	140.9	132.3	10.5
Beta Transus 1800-1820F			" "	-	140.4	129.7	13.0(1)
			1000F-25 Ksi-150 Hrs	0.035	136.4	129.9	2.0(2)
			" " "	0.058	122.7	Broke before YS(1,3)	
		1650F (2 hrs) AC	None	-	130.8	118.7	22.0
			800F - 150 Hrs	-	131.5	126.0	2.5
			800F-65 Ksi-150 Hrs	0.000	130.5	126.2	(2)
			" " "	0.000	119.0	114.0	1.0(1,3)
			900F - 150 Hrs	-	137.6	129.7	2.0
	(0.074% O_2, 45 ppm H_2)		900F-45 Ksi-150 Hrs	0.000	134.6	126.5	4.0
			" " "	0.000	133.2	124.5	10.0(1,2)
			1000F - 150 Hrs	-	138.8	130.5	4.5
			" "	-	136.3	127.2	4.5(1,2)
			1000F-25 Ksi-150 Hrs	0.029	132.3	127.9	1.0
			" " "	0.022	122.1	122.1	2.0(1,3)
		1650F (2 hrs) FC to 1000F	None	-	139.9	128.7	7.0
			800F - 150 Hrs	-	139.4	127.7	5.0
			800F-65 Ksi-150 Hrs	0.12	104.3	Broke before YS	
			" " "	0.12	135.9	128.1	2.0(1)
			900F - 150 Hrs	-	134.2	126.9	5.0(2)
	(0.079% O_2, 95 ppm H_2)		900F-45 Ksi-150 Hrs	0.12	116.9	Broke before YS	
			" " "	0.12	122.5	" " "(1,2)	
			1000F - 150 Hrs	-	139.8	130.4	11.0(2)
			" "	-	139.2	128.3	9.0(1)
			1000F-25 Ksi-150 Hrs	0.056	129.1	129.1	0
			" " "	0.095	116.9	Broke before YS(1)	

(Continued)

TABLE 17. (Continued)

Sheet No.	Gage in	Heat Treatment	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
S-3791	0.090	1650F (1/2 hr) AC	None	-	133.4	123.2	21.0
			800F - 150 Hrs	-	135.1	131.1	25.5
(6.86% Al, 11.10% Zr*,			800F-70 Ksi-150 Hrs	0.090	134.0	132.5	18.0(2)
0.09% O_2, 50 ppm H_2)			" " "	0.065	132.6	131.4	2.5(2)
			900F - 150 Hrs	-	138.2	131.5	15.0
	(0.086% O_2, 62 ppm H_2)		900F-55 Ksi-150 Hrs	0.047	135.6	127.7	7.0
			" " "	0.054	127.4	Broke before YS	0 (1)
Beta Transus >1820F			1000F - 150 Hrs	-	140.0	130.6	14.0
			" "	-	140.1	130.4	18.0(1)
			1000F-25 Ksi-150 Hrs	0.032	129.7	129.7	0
			" " "	0.041	138.0	128.0	15.5(1)
		1650F (2 hrs) AC	None	-	130.5	118.8	21.0
			800F - 150 Hrs	-	131.0	125.2	15.0
			800F-70 Ksi-150 Hrs	0.12	132.1	130.8	9.5
			" " "	0.23	129.9	129.1	2.5(1)
			900F - 150 Hrs	-	135.5	127.4	17.0
	(0.069% O_2, 41 ppm H_2)		900F-55 Ksi-150 Hrs	0.058	133.2	126.5	5.0
			" " "	0.010	133.4	125.8	3.5(1,2)
			1000F - 150 Hrs	-	137.3	127.0	11.0
			" "	-	135.7	124.3	15.0(1)
			1000F-25 Ksi-150 Hrs	0.040	134.8	125.3	(2)
			" " "	0.042	119.6	119.3	2.0(1,3)
		1650F (2 hrs) FC to 1000F	None	-	135.4	126.1	18.0
			800F - 150 Hrs	-	135.0	125.3	20.0
			800F-70 Ksi-150 Hrs	0.17	135.7	129.0	3.0
			" " "	0.16	130.6	127.8	4.0(1)
			900F - 150 Hrs	-	134.6	125.0	20.0
	(0.081% O_2, 84 ppm H_2)		900F-55 Ksi-150 Hrs	0.22	137.8	127.5	3.0
			" " "	0.19	125.6	124.5	1.5(1)

(Continued)

TABLE 17. (Continued)

Sheet No.	Gage in	Heat Treatment	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
			1000F - 150 Hrs	-	135.5	125.9	16.0
			" "	-	134.7	125.5	18.0(1)
			1000F-25 Ksi-150 Hrs	0.054	127.2	125.4	2.0
			" " "	0.083	137.9	126.4	10.5(1)

* Zirconium analyses performed before refinements made in analytical technique(3); values estimated to be approximately 10 percent low.

(1) Acid pickled 0.003in from gage after stability exposure but prior to tensile testing; all others tensile tested as-exposed without surface conditioning or pickling.

(2) Broke at end of gage length.

(3) Specimen pitted and/or too thin to obtain satisfactory test results.

The stability results, both stressed and unstressed, in Table 16 for Ti-5Al-5Sn-5Zr at 800-1000F show that no substantial stability problem exists in this alloy, although small ductility losses were observed for certain sheets and conditions. For example, a few specimens from the 0.020in material (S-3792), which contained 156 ppm hydrogen (although individual specimens analyzed 65-110 ppm hydrogen), suffered some slight loss in elongation after exposure, but no indication of serious instability was exhibited. Also, no instability was observed after simulated vacuum annealing at 1650F (2 hrs) FC to 1000F.

Regarding trends in creep of Ti-5Al-5Sn-5Zr, annealing at 1650F (2 hrs) AC provided somewhat better creep resistance than 1650F (1/2 hr) AC, with 1650F (2 hrs) FC to 1000F exhibiting appreciably greater creep deformation values. Of interest in the creep resistance at 800F is the much lower deformation obtained by lowering the stress level from 65 to 60 Ksi, which correspond to values slightly above and below the 0.2 percent yield strength at 800F, respectively. It should also be noted that at 800F, the creep resistance of 1650F (1/2 hr) AC annealed specimens was somewhat better at both 60 and 65 Ksi than samples annealed at 1650F (2 hrs) AC. This phenomenon probably results from the slightly lower strength obtained from the latter annealing treatment which is reflected as a slightly lower yield strength at 800F and, therefore, according to the creep deformation observation above, would result in a somewhat higher value of plastic deformation at 800F-60/65 Ksi.

Stability properties in Table 17 show that stability of Ti-7Al-12Zr sheet continues to be a problem, although at the outset it should be noted that one of the panels (S-3795) contained an abnormally high oxygen level of 0.10-0.12 percent. No doubt this had a pronounced influence on the stability of S-3795, since the ductility loss in this panel after exposure was much greater than for S-3791 which analyzed 0.09 percent oxygen. Thermal stability (without stress) of all three sheets was tolerable, at least as annealed at 1650F (1/2 hr) AC, although the loss in tensile elongation increased as the exposure temperature was raised from 800 to 1000F. Annealing at 1650F (2 hrs) AC produced a general deterioration in exposed properties compared to the shorter annealing time of 0.5 hour, but this degradation was much more severe in the two higher oxygen panels. The actual loss of ductility in samples annealed at 1650F (2 hrs) FC to 1000F after exposure in many instances was not any greater than specimens annealed at 1650F for 0.5 or 2 hours, and in the case of S-3791 this loss was somewhat smaller. However, the unexposed elongation of furnace cooled material was generally lower than after air cooling for the 1650F annealing cycle. Some surface instability was also

observed in a few samples (where a comparison could be made), as indicated by acid pickling 0.003in from gage after exposure. Pickling of specimens from Sheets S-3795 and S-3793 generally did not restore all of the original ductility, thus implying that some metallurgical instability had also been encountered in these two panels, one of which (S-3795) contained an abnormally high oxygen content.

Considering creep resistance, much the same trends were exhibited as for Ti-5Al-5Sn-5Zr described above. Creep deformation at 800F appeared to be somewhat lower after annealing at 1650F (1/2 hr) AC compared to 1650F (2 hrs) AC. Again, this is probably the result of the slightly higher 800F yield strength obtained by annealing for the shorter time. At 900 and 1000F there was little choice in creep resistance between the two annealing times. However, the simulated vacuum annealing cycle of 1650F (2 hrs) FC to 1000F provided inferior creep resistance at 800-1000F.

Based on this phase of the investigation, it is concluded that Ti-5Al-5Sn-5Zr possesses much better stability at 800-1000F than Ti-7Al-12Zr and is also far more tolerant of interstitial contaminants. Ti-5Al-5Sn-5Zr containing up to 0.09 percent oxygen or 150 ppm hydrogen exhibited little instability while Ti-7Al-12Zr with 0.07-0.10 percent oxygen was generally quite unstable. Of the three annealing cycles studies, 1650F (1/2 hr) AC and 1650F (2 hrs) FC to 1000F offered the best stability in Ti-7Al-12Zr, although the latter provided appreciably inferior creep resistance and also slightly lower unexposed tensile elongation. Of these two annealing treatments, 1650F (1/2 hr) AC is considered optimum for both alloys because of the better creep resistance, good stability, and its simplicity.

Property Evaluation of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr Sheets at Various Temperatures

In a study to compare the various sheet properties of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr with those of Ti-8Al-1Mo-1V presented in the Eleventh Bimonthly Report[3], samples were cut from two initially rolled sheets of each alloy (these had been finished as mill annealed at 1350F for 8 hours), thoroughly acid pickled, laboratory annealed, and tested at several temperatures. Included were standard room- and elevated-temperature tensile, sub-zero temperature notch tensile, and 800-1200F stability tests. Material from a fully mill processed sheet of 0.080in Ti-5Al-5Sn-5Zr was also given creep-stability tests at 800-1000F.

Results of sub-zero temperature notch tensile and standard elevated-temperature tests are presented in Tables 18 and 19 for Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, respectively. Included in these tables for comparison are earlier notch and unnotched tensile properties at -65F which were previously listed in Tables 4 and 5 of the Ninth Bimonthly Report(2). These data show that the notch tensile strength of 1350F mill annealed Ti-5Al-5Sn-5Zr sheet was comparable to that of 1650F (1/2 hr) AC annealed specimens, although at -320F and K_t=8.0 the latter annealing treatment produced much higher notch strength (NSR=1.10). Unfortunately, -110 and -320F unnotched tensile properties of both alloys in the 1350F mill annealed condition are not available due to a shortage of material from the two sheets. Somewhat comparable notch strengths were also observed in Ti-7Al-12Zr (Table 19) after mill annealing at 1350F (8 hrs) and after 1650F (1/2 hr) AC, although the latter provided better notch characteristics at the higher values of K_t. Based on the results of single test specimens, the notch strength (and notch strength ratio) dropped to very low levels at -320F and K_t=8.0, although good notch properties were exhibited by Ti-7Al-12Zr at -110F and room temperature. Thus, it appears that Ti-5Al-5Sn-5Zr offers considerably better cryogenic properties than Ti-7Al-12Zr, although a portion of this advantage may be related to the fact that the latter possesses somewhat higher strength at room temperature.

The elevated-temperature tensile properties of both alloys (Tables 18 and 19) show the rather minor effect of duplex annealing (1650F (1/2 hr) AC + 1100-1300F) on strength. Of the three duplexing cycles used, 1650F (1/2 hr) AC + 1100F (16 hrs) was the most effective, but even so the elevated-temperature strength was raised no more than 2-3 Ksi compared to 1650F simple annealing. A minor trend of decreasing strengths with increased stabilizing temperature (1100-1300F) was also observed for both alloys. Over the range of temperatures investigated (600-1000F) the yield strength of Ti-7Al-12Zr was 12-15 Ksi higher than that of Ti-5Al-5Sn-5Zr.

Thermal- (unstressed) and creep-stability properties of two heavier sheets, which were the initial ones finish rolled from 1750F, are listed in Tables 20 and 21. Again, as shown in Table 20, there was no stability problem with Ti-5Al-5Sn-5Zr even at exposure temperatures as high as 1200F. Of interest in this respect is the fact that little or no loss in ductility was encountered during 1200F-150 hours exposure, although the oxide scale was not removed. This same observation was also made on Ti-7Al-12Zr (Table 21), a phenomenon which was entirely unexpected. Good stability was also achieved in Ti-7Al-12Zr at 1100F, both stressed and unstressed, but considerable

TABLE 18. STANDARD AND NOTCH TENSILE PROPERTIES OF Ti-5Al-5Sn-5Zr SHEET AT VARIOUS TEMPERATURES
(V-1540, finish rolled from 1750F, mill annealed at 1350F (8 hours), ground and pickled, and laboratory tested as indicated; averages of duplicate longitudinal tests)

Heat Treatment	Test Temp,F	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	Notch Properties* K_t	Notch Properties* NTS Ksi	Notch Properties* NSR
Sheet A-4801, 0.062in							
As Mill Annealed (1350F - 8 hrs)	-320	-	-	-	3.0	253.3	-
	"	-	-	-	6.0	197.4	-
	"	-	-	-	8.0	176.3	-
	-110	-	-	-	3.0	189.2	-
	"	-	-	-	6.0	181.3	-
	"	-	-	-	8.0	176.1	-
	-65	143.8	138.7	23.8	3.0	179.1	1.24
	"	-	-	-	6.0	167.0	1.16
	RT	126.7	123.1	19.0	3.0	164.7	1.30
	"	-	-	-	6.0	158.7	1.25
	"	-	-	-	8.0	156.9	1.24
1650F (1/2 hr) AC	-320	198.9	182.3	14.0	3.0	243.3	1.22
	"	-	-	-	6.0	-	-
	"	-	-	-	8.0	218.4	1.10
	-110	146.8	133.0	23.0	3.0	185.4	1.26
	"	-	-	-	6.0	-	-
	"	-	-	-	8.0	177.2	1.21
	-65	140.2	126.3	15.0	3.0	172.9	1.23
	"	-	-	-	6.0	170.7	1.22
	RT	124.3	111.8	19.5	3.0	160.8	1.29
	"	-	-	-	6.0	154.4	1.24
	"	-	-	-	8.0	153.2	1.23
	600	91.5	67.4	26.0**	-	-	-
	700	88.8	64.9	25.3**	-	-	-
	800	85.0	62.8	24.5**	-	-	-
	900	82.4	62.3	25.5**	-	-	-
	1000	82.5	61.8	23.5**	-	-	-

(Continued)

TABLE 18. (Continued)

Heat Treatment	Test Temp, F	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	Notch Properties* K_t	Notch Properties* NTS Ksi	Notch Properties* NSR
1650F (1/2 hr) AC + 1100F (16 hrs)	RT	122.3	116.0	17.5**	-	-	-
	600	90.3	68.3	25.5**	-	-	-
	800	85.3	65.0	25.5**	-	-	-
	1000	80.3	62.0	25.5**	-	-	-
1650F (1/2 hr) AC + 1200F (8 hrs)	RT	122.7	113.2	17.0**	-	-	-
	600	90.2	67.6	24.0**	-	-	-
	800	84.2	63.3	26.5**	-	-	-
	1000	80.5	62.2	25.5**	-	-	-
1650F (1/2 hr) AC + 1300F (8 hrs)	RT	121.9	113.0	18.0**	-	-	-
	600	89.5	68.1	24.5**	-	-	-
	800	84.4	63.8	28.0**	-	-	-
	1000	79.7	60.7	25.0**	-	-	-

* Notch Specimen - 0.500in gage width, 0.250in notch width.
For K_t = 3.0, notch radius = 0.020in
K_t = 6.0, " " = 0.005in
K_t = 8.0, " " = 0.0025in

NTS - Notch Tensile Strength
NSR - Notch - Unnotch Strength Ratio

** Elongation measured in standard 2in gage length specimen; all others measured in 1in gage length sample.

TABLE 19. STANDARD AND NOTCH TENSILE PROPERTIES OF Ti-7Al-12Zr SHEET AT VARIOUS TEMPERATURES (V-1541, finish rolled from 1750F, mill annealed at 1350F (8 hrs), ground and pickled, and laboratory treated as indicated; averages of duplicate longitudinal tests)

Heat Treatment	Test Temp, F	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	Notch Properties* K_t	NTS Ksi	NSR
Sheet A-4802, 0.062in							
As Mill Annealed (1350F - 8 hrs)	-320	-	-	-	3.0	281.7	-
	"	-	-	-	6.0	196.1	-
	"	-	-	-	8.0	148.1	-
	-110	-	-	-	3.0	219.4	-
	"	-	-	-	6.0	208.3	-
	"	-	-	-	8.0	166.7	-
	-65	166.5	160.2	11.0	3.0	209.8	1.26
	"	-	-	-	6.0	187.4	1.13
	RT	149.7	143.7	13.8	3.0	197.9	1.32
	"	-	-	-	6.0	180.2	1.20
	"	-	-	-	8.0	165.9	1.11
1650F (1/2 hr) AC(1)	-320	219.0	198.9	7.0	3.0	255.4	1.17
	"	-	-	-	6.0	197.7	0.90
	"	-	-	-	8.0	148.2	0.68
	-110	155.2	141.8	13.0	3.0	205.1	1.32
	"	-	-	-	6.0	188.0	1.21
	"	-	-	-	8.0	191.6	1.23
	-65	149.9	136.7	13.3	3.0	193.9	1.29
	"	-	-	-	6.0	184.0	1.23
	RT	133.0	124.4	18.8	3.0	180.3	1.35
	"	-	-	-	6.0	173.3	1.30
	"	-	-	-	8.0	171.0	1.29
	600	98.3	81.2	27.3**	-	-	-
	700	94.5	78.7	25.5**	-	-	-
	800	93.1	77.9	23.0**	-	-	-
	900	88.7	75.6	27.3**	-	-	-
	1000	86.0	74.3	24.5**	-	-	-

(Continued)

TABLE 19. (Continued)

Heat Treatment	Test Temp, F	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %	Notch Properties* K_t	Notch Properties* UTS Ksi	Notch Properties* NSR
1650F (1/2 hr) AC + 1100F (16 hrs)	RT	131.3	122.5	17.0**	-	-	-
	600	100.2	83.9	24.5**	-	-	-
	800	94.9	80.3	22.0**	-	-	-
	1000	90.8	77.0	23.5**	-	-	-
1650F (1/2 hr) AC + 1200F (8 hrs)	RT	130.8	124.0	17.0**	-	-	-
	600	95.7	81.2	25.5**	-	-	-
	800	91.0	76.7	27.5**	-	-	-
	1000	85.2	72.8	24.5**	-	-	-
1650F (1/2 hr) AC + 1300F (8 hrs)	RT	130.6	126.0	18.0**	-	-	-
	600	95.2	80.9	27.0**	-	-	-
	800	90.7	76.6	26.5**	-	-	-
	1000	84.7	72.4	24.0**	-	-	-

* Notch Specimen - 0.500in gage width, 0.250in notch width
For K_t = 3.0, notch radius = 0.020in
K_t = 6.0, " " = 0.005in
K_t = 8.0, " " = 0.0025in

NTS - Notch Tensile Strength
NSR - Notch-Unnotch Strength Ratio

** Elongation measured in standard 2in gage length specimen; all others measured in 1in gage length sample.

(1) Notch and Unnotched properties at room temperature, -110, and -320F are the result of testing single specimens.

TABLE 20. THERMAL AND CREEP-STABILITY PROPERTIES OF Ti-5Al-5Sn-5Zr SHEET
(V-1540, A-4814, 0.090in, finish rolled from 1750F, mill annealed at 1350F (8 hrs), ground and pickled, and laboratory annealed at 1650F (1/2 hr) AC; longitudinal specimens, 0.072% O_2 and 30 ppm H_2)

Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
Not Exposed	-	122.1	111.8	20
800F - 100 Hrs	-	121.4	115.5	25
" "	-	120.4	115.2	25*
800F - 65 Ksi - 150 Hrs	0.41	123.9	123.3	24
" " "	0.47	120.6	118.4	16*
900F - 100 Hrs	-	123.9	119.6	24
" "	-	123.2	117.8	26*
900F - 45 Ksi - 150 Hrs	0.028	122.3	117.1	24
" " "	0.025	109.8(1)	104.9(1)	24*
1000F - 100 Hrs	-	124.2	118.4	21
" "	-	123.0	117.0	23*
1000F - 25 Ksi - 150 Hrs	0.035	123.9	116.4	17.5
" " "	0.028	122.3	114.5	23*
1100F - 100 Hrs	-	122.9	115.1	17
" "	-	122.0	114.2	19*
1100F - 10 Ksi - 150 Hrs	0.051	123.2	115.6	21
" " "	0.054	120.3	112.5	19*
1200F - 100 Hrs	-	122.5	113.9	19
" "	-	94.9(1)	88.2(1)	24*

* Acid pickled 0.003in from gage after exposure; all others tensile tested as-exposed.

(1) Low values probably due to error in specimen measurement.

TABLE 21. THERMAL AND CREEP-STABILITY PROPERTIES OF Ti-7Al-12Zr SHEET (V-1541, A-4809, 0.090in, finish rolled from 1750F, mill annealed at 1350F (8 hrs), ground and pickled, and laboratory annealed at 1650F (1/2 hr) AC; longitudinal specimens, 0.073% O_2 and 32-40 ppm H_2)

Stability Exposure	O_2 %	H_2 ppm	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
Not Exposed	-	-	-	133.3	120.3	20.5
800F - 100 Hrs	-	-	-	132.3	127.3	25
" "	-	-	-	132.2	126.2	25*
800F - 65 Ksi - 150 Hrs	-	-	0.00	134.2	130.0	6.5
" " "	-	-	0.00	135.2	129.9	(1)*
900F - 100 Hrs	-	-	-	136.9	130.1	7
" "	-	-	-	135.8	128.5	20*
900F - 45 Ksi - 150 Hrs	0.095	32	0.01	136.4	127.4	7
" " "	-	-	0.00	136.9	122.1	24*
1000F - 100 Hrs	-	-	-	139.7	129.7	9
" "	-	-	-	138.1	127.4	21*
1000F - 25 Ksi - 150 Hrs		-	0.031	137.1	128.1	5
" " "	-	-	0.019	125.6	125.6	2*(2)
1100F - 100 Hrs	-	-	-	138.6	127.0	14
" "	-	-	-	139.6	127.9	19*
1100F-10 Ksi-150 Hrs	0.076	35	0.025	138.7	130.7	14.5
" " "	-	-	0.038	139.2	128.4	19*
1200F - 100 Hrs	-	-	-	134.1	124.6	16
" "	-	-	-	134.7	123.5	21*

* Acid pickled 0.003in from gage after exposure; all others tensile tested as-exposed with no surface conditioning.

(1) Broke outside of gage length.

(2) Pitted pickled surface; results questionable.

instability was encountered as exposed at 800-1000F. Good thermal (unstressed) stability was observed at 800F, but not under stress, while at 900 and 1000F relatively poor stability was indicated for both types of tests. Practically all of the instability obtained in unstressed samples was of the surface variety, since acid pickling after exposure restored the original tensile elongation. However, acid pickling after creep exposure at 1000F did not improve the ductility, although this specimen was pitted and the results may be questionable.

Excellent creep resistance was provided by both alloys, even at 1100F, although the 10 Ksi stress level used is not particularly high. Again, the difference in creep deformation between the two compositions at 800F-65 Ksi-150 hours was quite pronounced, since 65 Ksi is above the 800F yield strength in Ti-5Al-5Sn-5Zr and below it in Ti-7Al-12Zr. The latter alloy also exhibited somewhat better creep resistance at 900-1100F for the stress levels used.

Photomicrographs of both alloys are shown in Figures 10 through 13, illustrating the effects of 1000F creep-stability tests and a stabilizing treatment of 1300F (8 hrs) on the microstructure. Of particular interest is the comparison of Ti-7Al-12Zr in Figures 10 and 11, in which the latter had been exposed to 1000F-25 Ksi-150 hours. As a result of this exposure, the grains possessed a rougher appearance and general precipitation had occurred at the grain boundaries compared to the unexposed structure of Figure 10. This reaction seems to explain for the most part why Ti-7Al-12Zr generally exhibits inferior stability, since the structure of creep-exposed Ti-5Al-5Sn-5Zr (Figure 13) contained only minor quantities of grain-boundary precipitate. More globular precipitate of larger particle size is seen (Figure 12) in Ti-7Al-12Zr which had been given 1300F (8 hrs) after annealing at 1650F.

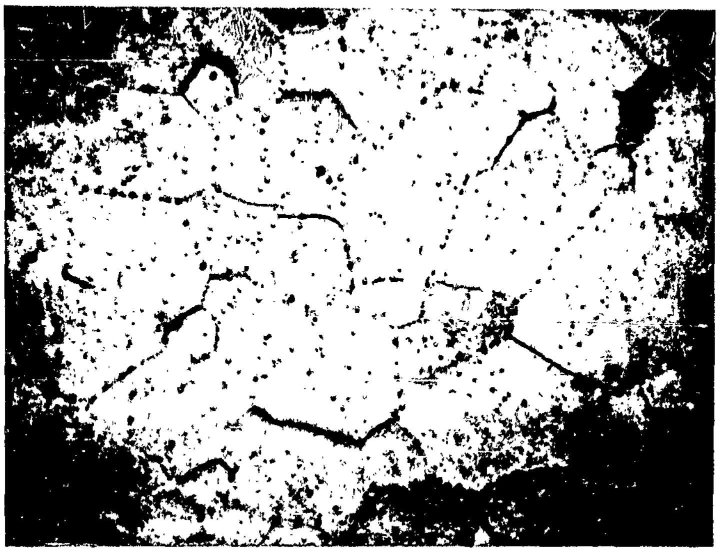
Thermal and creep-stability properties of a fully mill processed sheet of Ti-5Al-5Sn-5Zr (V-1813F, 0.080in) are presented in Table 22, showing the excellent stability and creep resistance available in this alloy. Two stress levels were used at 800F, 60 and 65 Ksi, thus bracketing the yield strength at this temperature (61.9 Ksi) to illustrate the pronounced differences in creep deformation which can be obtained by relatively small changes in stress level. Increased creep deformation also resulted at 1000F as the stress was raised from 25 to 35 Ksi, but even at the highest stress of 35 Ksi, the deformation was a very respectable value of 0.15 percent.

61-84-C OBLIQUE LIGHT 500X

FIGURE 10. Ti-7Al-12Zr, 0.090in, V-1541, SHEET A-4809, LONGITUDINAL SECTION, 1650F (2 HRS) AC. NOTE ABSENCE OF GENERAL GRAIN-BOUNDARY PRECIPITATE.

61-84-D OBLIQUE LIGHT 500X

FIGURE 11. Ti-7Al-12Zr, 0.090in, V-1541, SHEET A-4809, LONGITUDINAL SECTION. 1650F (2 HRS) AC + CREEP TESTED AT 1000F-25 Ksi-150 HRS. GENERAL GRAIN BOUNDARY PRECIPITATION AND ROUGHENED GRAINS COMPARED TO FIGURE 10.



61-85-H OBLIQUE LIGHT 500X

FIGURE 12. Ti-7Al-12Zr, 0.062in, V-1541, SHEET A-4802, LONGITUDINAL SECTION. 1650F (1/2 HR) AC + 1300F (8 HRS). GENERAL GRAIN BOUNDARY PRECIPITATE.

61-86-H OBLIQUE LIGHT 500X

FIGURE 13. Ti-5Al-5Sn-5Zr, 0.062in, V-1540, SHEET A-4801, LONGITUDINAL SECTION. 1650F (1/2 HR) AC + CREEP TESTED AT 1000F-25 Ksi-150 HRS. ONLY MINOR AMOUNTS OF GRAIN BOUNDARY PRECIPITATE COMPARED TO FIGURE 11.

TABLE 22. THERMAL AND CREEP-STABILITY PROPERTIES OF FULLY MILL PROCESSED Ti-5Al-5Sn-5Zr SHEET (V-1813B, A-7064 Sheet No. 1, finish rolled from 1750F, mill annealed at 1350F (8 hrs), and finish annealed at 1650F (1/2 hr) AC; longitudinal specimens, 0.080in)

Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
None	-	126.3	114.7	14.5(1)
None (Tested at 800F)	-	85.7	61.9	27.5(1)
800F - 150 Hrs	-	125.3	120.3	24.0
" "	-	125.8	120.8	25.0(2)
800F - 60 Ksi - 150 Hrs	0.010	125.8	117.5	26.0
800F - 65 Ksi - 150 Hrs	0.17	125.1	120.6	25.0
900F - 150 Hrs	-	126.7	120.4	17.0
" "	-	126.5	119.5	22.0(2)
900F - 55 Ksi - 150 Hrs	0.083	127.4	121.0	24.5
1000F - 150 Hrs	-	126.5	120.4	12.0
" "	-	127.0	123.0	21.0(2)
1000F - 25 Ksi - 150 Hrs	0.025	127.3	118.3	22.0
1000F - 30 Ksi - 150 Hrs	0.058	127.1	117.9	20.0
1000F - 35 Ksi - 150 Hrs	0.15	124.8	114.2	21.5
(0.070% O_2, 47 ppm H_2)				

(1) Elongation measured in standard 2in gage length specimen.

(2) Acid pickled 0.003in from gage after exposure; all others tensile tested as-exposed without any surface conditioning.

Uniformity of Properties Within Sheets of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr

This investigation was established as a companion program to that made on Ti-8Al-1Mo-1V sheet, which was discussed in a previous section of the report. A typical 0.062in sheet of each alloy was selected from the first two ingots (V-1540 and V-1541) which had been fully processed through all mill operations and were established as optimum procedures for both compositions. In other words, the sheets were finish rolled from 1750F, mill annealed at 1350F (8 hrs), rough ground, final annealed at 1650F (1/2 hr) AC, finish ground, and pickled. Mill test results for these sheets are included in a later section of this report.

The two sheets were sampled at four 9 x 18in locations according to the sampling plan depicted in Tables 23 through 26 and room-temperature tensile and bend, 800 and 1000F tensile, and 800-1000F creep-stability properties were measured in these locations. Results of this study are also listed in Tables 23 through 26, which show that the room- and elevated-temperature tensile properties were quite uniform throughout both sheets. As has been obvious in preceding sections of the report, the room-temperature strength of Ti-7Al-12Zr was approximately 10 Ksi higher than that of Ti-5Al-5Sn-5Zr and at 800 and 1000F this difference had increased to the order of 15-20 Ksi. However, the room-temperature tensile elongation and bendability of Ti-5Al-5Sn-5Zr were slightly greater than measured in Ti-7Al-12Zr. Values of modulus of elasticity are also given in Tables 23 and 24 showing that the elastic modulus of Ti-7Al-12Zr was about 0.5-1.0 x 10^3 Ksi higher than that of Ti-5Al-5Sn-5Zr at room and elevated temperatures.

As in the Ti-8Al-1Mo-1V uniformity study (see Tables 3 and 4), creep-stability tests were conducted on the Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheets primarily in two locations, Panels A-3 and C-2 (see Tables 25 and 26). However, these were performed in duplicate at 800 and 1000F and, in order to gain additional information on creep deformation at varying stress levels at 900 and 1000F, a few samples were also tested from Panels C-1 and E-2. As listed in Table 25, the stability of the Ti-5Al-5Sn-5Zr sheet was excellent at all three temperatures. The creep resistance in the temperature range, 800-1000F, was also excellent with 0.1 percent deformation or less being consistently achieved for all exposure conditions except 900F-60 Ksi-150 hours (0.22 percent creep deformation). Good agreement was also obtained with the creep data presented in Table 22 for another fully mill processed sheet, although

TABLE 23. UNIFORMITY OF TENSILE AND BEND PROPERTIES THROUGHOUT A TYPICAL SHEET OF Ti-5Al-5Sn-5Zr (V-1540B, A-6749 Sheet No. 3, 0.058 x 37 x 68in; finish rolled from 1750F, mill annealed at 1350F (8 hrs), and finish annealed at 1650F (1/2 hr)AC)

Sheet (1) Location	O_2 %	H_2 ppm	Test Temp, F	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	Modulus of Elasticity, 10^3 Ksi	MBR, (2) T
A-3	-	-	RT	L	123.6	114.2	20.0	15.6	3.6
	0.083	98	RT	T	120.9	111.5	20.5	16.0	3.3
C-1	-	-	RT	L	123.6	111.9	20.5	15.7	3.6
	-	-	RT	T	121.0	112.6	19.5	16.3	3.6
C-2	-	-	RT	L	124.3	115.5	20.0	15.7	3.3
	0.072	117	RT	T	121.3	115.8	20.5	16.0	3.3
E-2	-	-	RT	L	123.3	113.8	19.5	15.6	3.6
	-	-	RT	T	123.1	115.8	11.0(3)	16.8	3.6
A-3	-	-	800	T	79.4	61.7	29.0	13.0	-
	-	-	1000	T	75.6	60.2	27.5	10.7	-
C-1	-	-	800	T	79.2	65.2	31.0	12.7	-
	-	-	1000	T	75.9	61.0	28.0	11.1	-
C-2	-	-	800	T	79.5	62.1	29.0	12.9	-
	-	-	1000	T	76.4	61.2	28.5	11.4	-
E-2	-	-	800	T	80.4	62.6	30.0	12.9	-
	-	-	1000	T	76.9	61.4	29.5	11.7	-

(1) Sampling plan to obtain four 9 x 18in panels.

(2) Minimum press brake bend radius at 20X inspection.

(3) Broke at end of gage length.

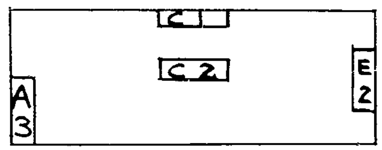


TABLE 24. UNIFORMITY OF TENSILE AND BEND PROPERTIES THROUGHOUT A TYPICAL SHEET OF Ti-7Al-12Zr
(V-1541T, A-6574 Sheet No. 5, 0.060 x 36 x 99in; finish rolled from 1750F, mill annealed at 1350F (8 hrs), and finish annealed at 1650F (1/2 hr) AC)

Sheet (1) Location	O_2 %	H_2 ppm	Test Temp,F	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	Modulus of Elasticity, 10^3 Ksi	MBR,(2) T
A-3	-	-	RT	L	136.3	125.6	18.0	16.4	3.5
	0.077	68	RT	T	135.5	125.7	20.0	16.8	3.2
C-1	-	-	RT	L	134.5	123.8	17.0	16.4	3.7
	-	-	RT	T	134.8	123.7	18.0	16.7	3.7
C-2	-	-	RT	L	134.2	122.0	17.5	16.4	3.7
	0.058	38	RT	T	135.0	124.0	18.5	16.9	3.7
E-2	-	-	RT	L	135.3	123.3	17.5	16.4	3.7
	-	-	RT	T	135.7	125.4	19.5	16.8	3.7
A-3	-	-	800	T	98.1	78.5	26.5	14.3	-
	-	-	1000	T	94.3	75.4	22.0	13.8	-
C-1	-	-	800	T	97.8	77.8	26.0	13.4(3)	-
	-	-	1000	T	94.9	74.9	29.5	13.6	-
C-2	-	-	800	T	97.2	77.5	27.0	12.7(3)	-
	-	-	1000	T	95.1	76.7	25.5	13.6	-
E-2	-	-	800	T	97.5	78.5	28.0	13.6	-
	-	-	1000	T	95.3	76.8	23.0	12.0(3)	-

(1) Sampling plan to obtain four 9 x 18in panels.

(2) Minimum press brake bend radius at 20X inspection.

(3) Value probably low because of faulty load-strain curve.

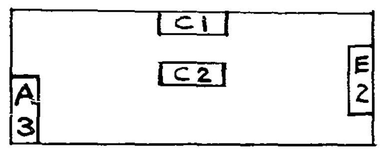


TABLE 25. CREEP-STABILITY PROPERTIES WITHIN A TYPICAL SHEET OF Ti-5Al-5Sn-5Zr (V-1540B, A-6749 Sheet No. 3, 0.058 x 37 x 68in; finish rolled from 1750F, mill annealed at 1350F (8 hrs), and finish annealed at 1650F (1/2 hr) AC)

Sheet Location (1)	Dir	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
A-3	T	800F - 60 Ksi - 150 Hrs	0.12	126.3	125.4	23.0
	T	" " "	0.065	125.2	121.2	22.5
	T	1000F - 30 Ksi - 150 Hrs	0.076	123.9	119.5	9.0(2)
	T	" " "	0.087	125.9	118.9	20.0
C-2	T	800F - 60 Ksi - 150 Hrs	0.13	126.8	123.6	25.0
	T	" " "	0.065	125.0	121.0	25.5
	T	1000F - 30 Ksi - 150 Hrs	0.098	125.1	119.7	23.5
	T	" " "	0.036	126.1	121.2	22.0
E-2	T	900F - 55 Ksi - 150 Hrs	0.10	126.1	124.3	22.0
	T	" " "	0.094	127.3	122.9	19.0
	T	900F - 60 Ksi - 150 Hrs	0.19	127.9	124.9	25.0
	T	" " "	0.24	126.4	126.0	23.5

(1) Sampling plan for the four 9 x 18in panels. All specimens tensile tested as exposed without surface pickling or conditioning.

(2) Broke at end of gage length.

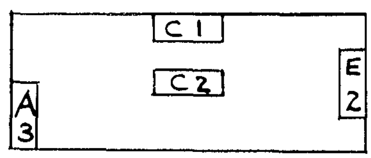
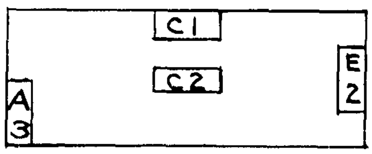


TABLE 26. CREEP-STABILITY PROPERTIES WITHIN A TYPICAL SHEET OF Ti-7Al-12Zr (V-1541T, A-6754 Sheet No. 5, 0.060 x 36 x 99in; finish rolled from 1750F, mill annealed at 1350F (8 hrs), and finish annealed at 1650F (1/2 hr) AC)

Sheet Location (1)	Dir	Stability Exposure	Creep Def,%	UTS Ksi	Y.S. (0.2%) Ksi	Elong (1in) %
A-3	T	800F - 70 Ksi - 150 Hrs	0.014	139.2	136.4	19.0(2)
	T	" " "	0.007	140.8	136.0	21.0
	T	1000F - 30 Ksi - 150 Hrs	0.15	143.6	132.6	10.0
	T	" " "	0.13	128.0	128.0	1.5(3)
C-1	T	1000F - 35 Ksi - 150 Hrs	0.11	140.8	132.5	4.0
	T	" " "	0.13	142.1	130.0	16.0(3)
C-2	T	800F - 70 Ksi - 150 Hrs	0.00	140.2	134.1	18.0
	T	" " "	0.014	137.6	131.8	4.0(2)
	T	1000F - 30 Ksi - 150 Hrs	0.094	144.5	135.3	8.0
	T	" " "	0.12	144.3	132.0	17.0(3)
E-2	T	900F - 55 Ksi - 150 Hrs	0.036	142.3	135.7	16.0(2)
	T	" " "	0.072	143.5	132.9	16.0
	T	900F - 65 Ksi - 150 Hrs	0.17	142.8	134.9	7.0
	T	" " "	0.17	143.4	134.8	15.5(3)

(1) Sampling plan for four 9 x 18in panels.



(2) Broke at end of gage length.

(3) Acid pickled 0.003in from gage after exposure, but prior to tensile testing at room temperature. All others tensile tested as exposed with pickling.

at 800F-60 Ksi-150 hours there appeared to be an appreciable difference. However, the stress level at this temperature is quite critical, since it approaches the 800F yield strength which can vary slightly from sheet to sheet and, therefore, this variance would markedly influence the plastic deformation of a given specimen.

Stability of the sheet of Ti-7Al-12Zr (Table 26) was excellent at 800F, fair to good at 900F, and marginal at 1000F, as measured by the loss of elongation in as-exposed samples. However, in nearly every case the elongation was restored by acid pickling after exposure. The stability at 900 and 1000F also appeared to be affected by the stress level, with more instability indicated at the higher stresses. However, this can only be established in a tentative fashion, because of the limited number of tests performed. The creep resistance of Ti-7Al-12Zr was excellent under the rather severe conditions utilized in this study. For example, deformations less than 0.02 percent were obtained at 800F-70 Ksi-150 hours, less than 0.10 percent at 900F-55 Ksi-150 hours, and no more than 0.15 percent at 1000F-30/35 Ksi-150 hours. Comparing the test condition of 900F-55 Ksi-150 hours, the creep resistance of the Ti-5Al-5Sn-5Zr sheet (Table 25) was slightly inferior to that of the sheet of Ti-7Al-12Zr in Table 26, while at 1000F-30 Ksi-150 hours, the creep properties of Ti-5Al-5Sn-5Zr held a slight advantage.

Stress Relieving Studies on Welded Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr Sheets

An additional investigation of the welded properties of fully mill processed sheets of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr was undertaken with the primary purpose of determining the various temperature-time combinations required to stress relieve both materials. This was performed on samples of unwelded sheet and the two more promising cycles were then applied to determine the effect of such stress relieving treatments on the properties of welded specimens.

The sheets used for the property uniformity study discussed in the previous section were also utilized for this investigation. Stress relief measurements were made on unwelded material by means of relaxation of restrained bend specimens, a procedure described for Ti-8Al-1Mo-1V in an earlier section of this report. Longitudinal bend samples, 3/4 x 5in, were sheared from the 0.062in sheets of Ti-5Al-5Sn-5Zr (V-1540B) and Ti-7Al-12Zr (V-1541T), bent around a 5T radius, restrained in the V-shaped fixture, and heated at 900-1300F for 0.25-90 hours.

Results of the relaxation measurements are depicted graphically in Figures 14 and 15 for Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, respectively, which show that at 900 and 1000F excessively long times were required to achieve substantial stress relief, while much shorter periods were necessary at 1100-1300F to effect a high degree of stress relief. Except for 1000 and 1300F, which displayed little differences, Ti-5Al-5Sn-5Zr stress relieved somewhat faster than Ti-7Al-12Zr, a phenomenon that might be expected because of the lower aluminum content.

Just as with Ti-8Al-1Mo-1V sheet, cycles at 1100 to 1300F were the only ones which produced substantially complete stress relief in reasonably short periods. Therefore, treatments for further study on welded material were selected from this temperature range. However, as indicated in the Eleventh Bimonthly Report(3), a postweld treatment of 1100F (1 hr) AC produced inferior weld properties, particularly in Ti-7Al-12Zr. Consequently, two practical stress relieving cycles for further study were selected for each alloy at 1200 and 1300F, only, as follows:

Ti-5Al-5Sn-5Zr	Ti-7Al-12Zr
1200F (3 hrs)	1200F (3 hrs)
1300F (1/2 hr)	1300F (3/4 hr)

Welded specimens of both compositions have been given the respective treatments above to determine the effect of each on the welded properties. However, this phase of the study is incomplete and, therefore, the data will be included in the Summary Report.

Comparison of the Stress Corrosion Behavior of Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr Sheet During Stress Relieving

In conjunction with the stress relieving studies performed on the three alloys in the contract, which were discussed in previous sections, it was felt that some information was required on the behavior of the three compositions in contact with salt during a stress relief treatment. To accomplish this, a laboratory test was used which has been effective in the past in indicating the susceptibility of a material to stress corrosion by salt during hot sizing or stress relieving. The test procedure consists of bending a 1in wide strip around a 4-5T radius, boiling for 10 minutes in

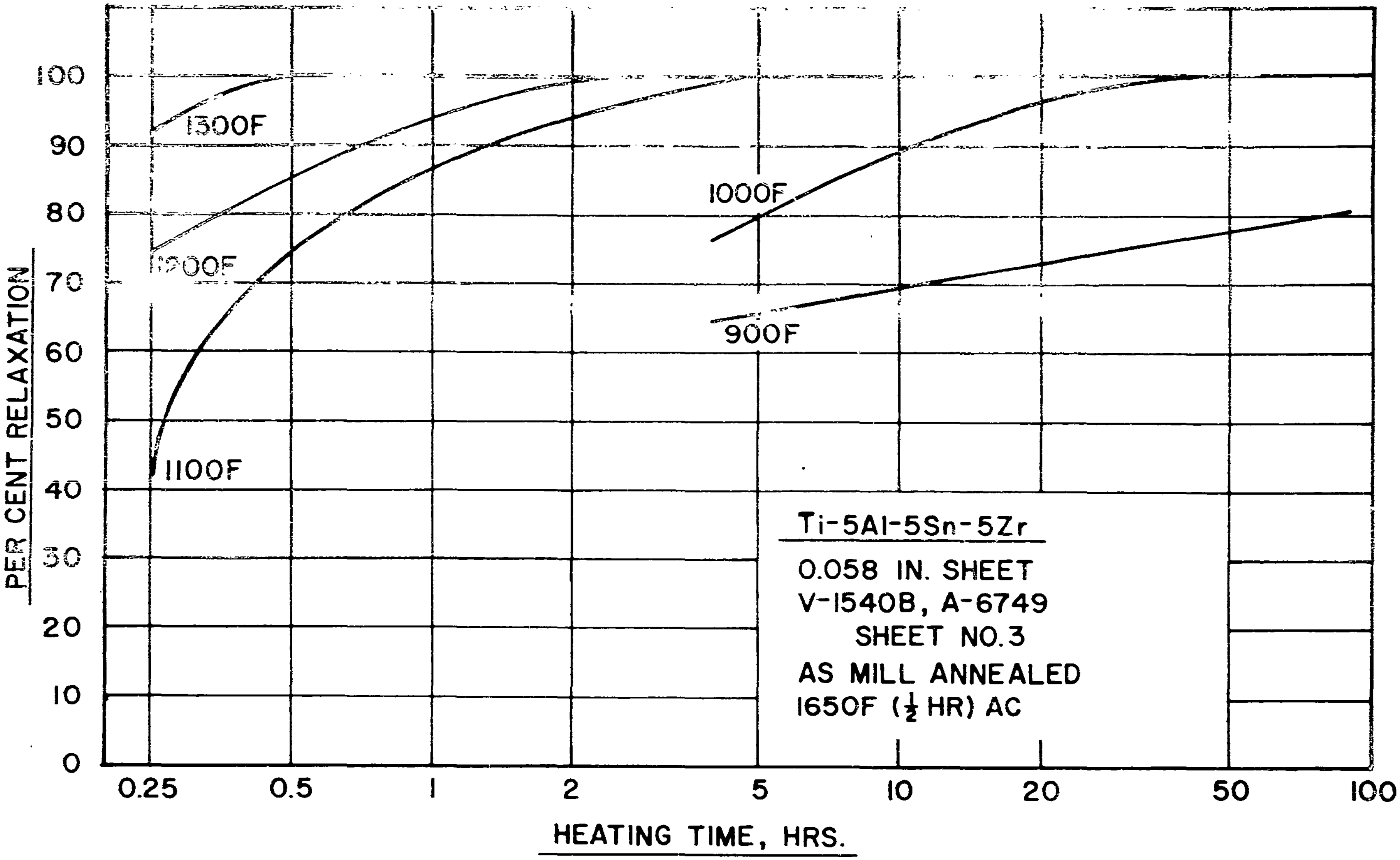


FIGURE 14. EFFECTS OF HEATING TIME AND TEMPERATURE ON THE RELAXATION OF RESTRAINED BEND SPECIMENS OF ANNEALED Ti-5Al-5Sn-5Zr SHEET.

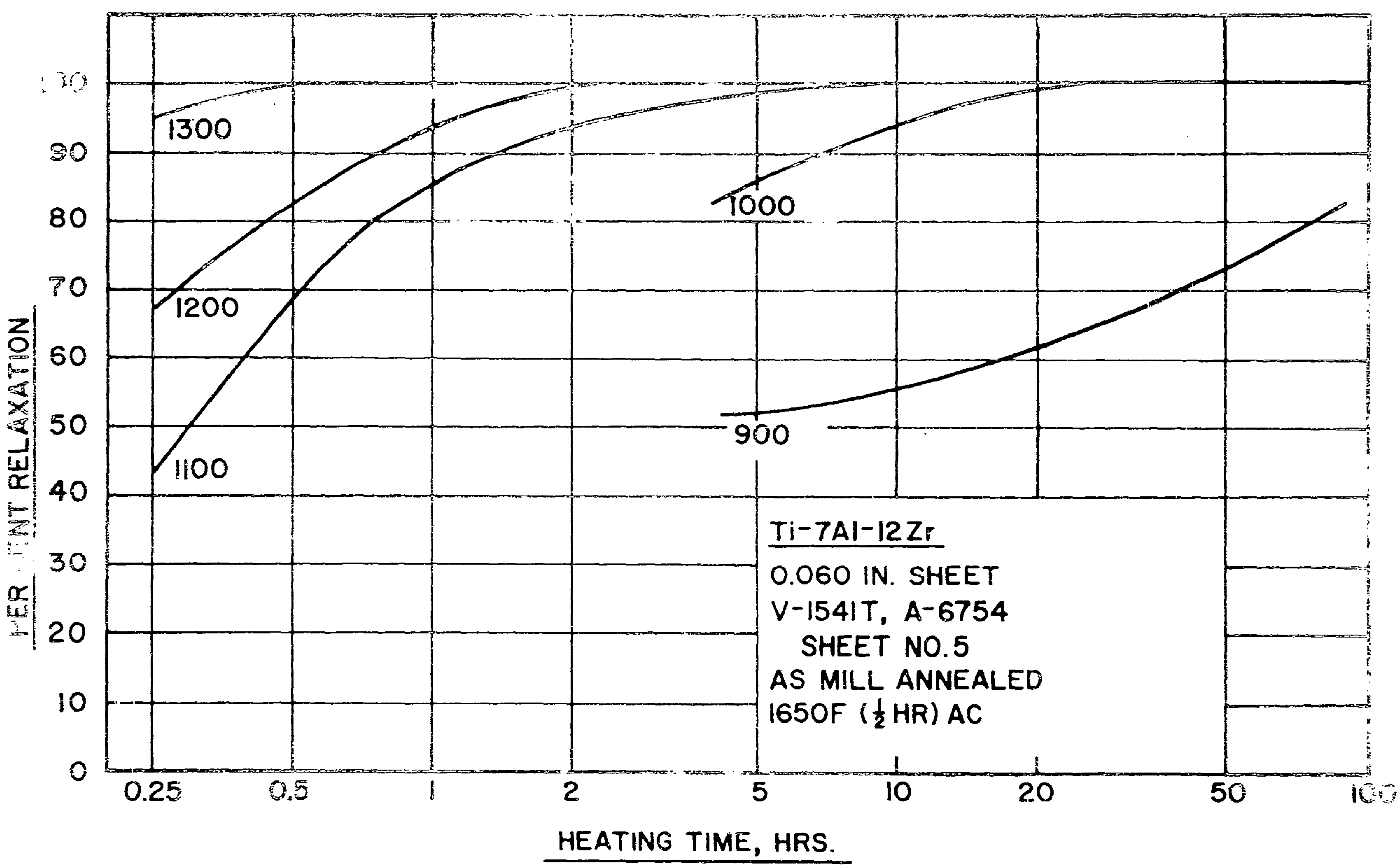


FIGURE 15. EFFECTS OF HEATING TIME AND TEMPERATURE ON THE RELAXATION OF RESTRAINED BEND SPECIMENS OF ANNEALED Ti-7Al-12Zr SHEET.

a saturated solution of sodium chloride, air drying, and then exposing the sample to 1100F for 1 hour. The cross-section of the concave or inside surface of the bent specimen is then examined metallographically for the number and depth of the cracks; obviously, the greater the number or depth of cracks, the more sensitive the material is to residual surface chlorides during stress relief.

Using this procedure, samples of Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr were tested using the previously-established annealing cycles. In addition, specimens from the latter two alloys were also given other alpha annealing treatments and an alpha-beta anneal to determine the effect of these other treatments on the stress corrosion behavior. Results of this investigation, which are listed in Table 27, show that Ti-8Al-1Mo-1V exhibited much greater resistance to cracking than the other two alloys. Of the two annealed conditions used on Ti-8Al-1Mo-1V, the duplex annealing treatment provided the most resistance, although neither was particularly susceptible to cracking.

Increased annealing temperature in the alpha field (below 1700-1725F) decreased the number of cracks in Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, although the severity, as measured by maximum depth, was not markedly affected. Alpha-beta annealing (1750F) resulted in a pronounced improvement in the stress corrosion resistance of Ti-5Al-5Sn-5Zr, but only to a minor extent in Ti-7Al-12Zr. However, as has been discussed in previous sections, alpha-beta annealing also lowers the creep resistance and the tolerance for hydrogen.

It should be emphasized that this study was performed concurrently with the stress relief investigation and, therefore, an exposure of 1100F (1 hr) was rather arbitrarily selected as one which would provide substantial relief of residual stresses. Referring to Figures 2 and 3 for Ti-8Al-1Mo-1V and Figures 14 and 15 for Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, it is seen that mill annealed Ti-8Al-1Mo-1V was nearly 100 percent stress relieved at 1100F (1 hr), while only 80-85 percent relaxation was obtained in duplex annealed Ti-8Al-1Mo-1V and the two alpha alloys. This may have had some effect on these stress corrosion observations.

Two items of interest should be noted at this point. First, prior work has shown that alpha-beta titanium alloys are much more resistant to stress corrosion cracking under the conditions used (exposure to 1100F for 1 hour) than the alpha alloys and, second, other stress relief - salt exposure temperatures might minimize or eliminate such cracking.

TABLE 27. COMPARISON OF THE STRESS CORROSION BEHAVIOR OF Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, AND Ti-7Al-12Zr SHEET DURING STRESS RELIEVING

(Except for the as-mill annealed condition, all materials were acid pickled and laboratory annealed as indicated; longitudinal bend samples (4.0T) coated with salt and exposed at 1100F for 1 hour)

Sheet No.	Gage in	Condition	Crack Rating* No. of Cracks	Crack Rating* Depth of Crack
Ti-8Al-1Mo-1V				
A-5473 No. 3 (V-1555)	0.075	As Mill Annealed (1450F - 4 hrs)	6-S	0.007in (9.3%) - S
	0.073	1850F (5 min) AC + 1100F (8 hrs)	1-VS	0.001in (1.4%) - VS
Ti-5Al-5Sn-5Zr				
A-4801 (V-1540)	0.068	As Mill Annealed (1350F - 8 hrs)	97-H	0.018in (26.4%) - H
		1450F (2 hrs) AC	79-H	0.018in (26.4%) - H
		1550F (1 hr) AC	74-H	0.012in (17.6%) - M
		1650F (1/2 hr) AC	68-H	0.020in (29.4%) - H
		1750F (1/2 hr) AC	21-M	0.005in (7.7%) - S
Ti-7Al-12Zr				
A-4802 (V-1541)	0.063	As Mill Annealed (1350F - 8 hrs)	128-H	0.014in (22.2%) - H
	0.063	1450F (2 hrs) AC	113-H	0.015in (23.8%) - H
	0.064	1550F (1 hr) AC	84-H	0.018in (28.1%) - H
	0.052	1650F (1/2 hr) AC	65-H	0.015in (28.8%) - H
	0.062	1750F (1/2 hr) AC	56-H	0.015in (24.2%) - H

* Crack Rating

None	-	0-1% maximum depth of cracking
VS	-	1-5% " " "
S	-	5-10% " " "
M	-	10-20% " " "
H	-	Greater than 20% maximum depth of cracking.

For example, it seems reasonable that if the exposure temperature were raised to say 1300F, the extent of cracking would diminish because the residual stresses would be relieved faster than salt-induced cracks could propagate. If so, this is a clear-cut advantage for stress relieving Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr at the highest practical temperatures. Obviously, additional studies in this area would be required to define the conditions necessary for minimizing the salt stress corrosion of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr and to determine the degree of cleanliness required in processing the two alloys by the consumer.

PROCESSING OF Ti-5Al-5Sn-5Zr AND Ti-7Al-12Zr

The 26 sheets of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, representing the balance of material from the first two heats (V-1540 and V-1541) and which had previously been finish annealed, ground, and pickled(3), were tensile and bend tested with properties as listed in Tables 28 and 29. Test results on the 12 sheets of Ti-5Al-5Sn-5Zr (Table 28) were quite consistent with good tensile and bend ductility values being achieved in each sheet. Only one piece of 0.062in material failed to meet a 4.0T minimum bend radius, probably as a result of some minor surface contamination remaining on the bend specimen. The only disturbing data in Table 28 are the high hydrogen levels obtained in the 0.020in sheets. The source of this pickup has not been pinpointed, but at least a portion of it was present after mill annealing at 1350F (8 hrs), since at that stage the hydrogen analyzed 150-160 ppm. Most of the contamination probably resulted from finish hot rolling. Additional pickup of 50-90 ppm was obtained in the finishing operations, most of which occurred during final annealing at 1650F (1/2 hr) AC. This potential problem will be closely followed in future processing of thin-gage Ti-5Al-5Sn-5Zr sheets, since every effort is being made to hold the hydrogen to a maximum of 150 ppm in this alloy.

Properties of the Ti-7Al-12Zr sheets in Table 29 were also consistent within each gage, but somewhat higher strengths were exhibited by the 0.020in material than the two heavier gages. It should be noted at this point that some flatness difficulty was encountered during final annealing the 0.020in sheets at 1650F (1/2 hr) AC, such that the edges curled during cooling. As a result, these sheets were very difficult to finish grind properly and no doubt some surface contamination remained at the edges where the test samples were taken. Consequently, the strengths are probably higher and certainly the ductility values are lower, particularly bendability, than would have otherwise been obtained. Also, the hydrogen content is higher than desired and certainly higher than the 40 ppm

TABLE 28. ROOM-TEMPERATURE TENSILE AND BEND PROPERTIES OF FULLY MILL PROCESSED Ti-5Al-5Sn-5Zr SHEETS (V-1540, finish rolled from 1750F, mill annealed at 1350F (8 hrs), finish annealed at 1650F (1/2 hr) AC, ground, and pickled)

Ingot Location	Gage in	Test No.	Sheet No.	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	MBR, T	H_2 ppm
Bottom	0.020	A-6751	1	L	127.9	114.6	16.5	3.0	240
		(S-3792)		T	-	-	-	-	-
			2	L	128.6	115.7	17.0	3.0	210
				T	124.3	114.4	14.5	3.2	-
			3	L	129.0	111.7	17.5	3.0	240
				T	125.1	111.4	18.5	3.2	-
			4	L	128.0	114.4	17.0	3.0	220
				T	125.1	111.9	20.5	3.2	-
Bottom	0.062	A-6749	1	L	126.4	116.1	16.5	3.6	110
		(S-3790)		T	125.7	116.4	13.5	4.1	-
			2	L	126.6	115.5	17.0	3.1	90
				T	-	-	-	-	-
			3	L	127.3	116.3	16.0	3.1	100
				T	123.4	114.3	16.5	3.6	-
			4	L	127.2	115.9	17.5	3.6	100
				T	125.8	114.7	17.5	3.8	-
Top	0.090	A-6575	1	L	127.4	117.2	16.0	3.1	90
		(S-3796)		T	122.4	112.1	17.5	3.1	-
			2	L	125.5	115.4	17.0	3.5	100
				T	124.1	114.4	16.5	3.1	-
			3	L	124.4	115.2	18.0	3.1	80
				T	123.9	113.6	17.5	3.1	-
		A-6750	2	L	126.4	116.0	16.0	3.3	60
		(S-3796)		T	124.0	114.5	17.5	3.3	-

TABLE 29. ROOM-TEMPERATURE TENSILE AND BEND PROPERTIES OF FULLY MILL PROCESSED Ti-7Al-12Zr SHEETS (V-1541, finish rolled from 1750F, mill annealed at 1350F (8 hrs), finish annealed at 1650F (1/2 hr) AC, ground, and pickled)

Ingot Location	Gage in	Test No.	Sheet No.	Dir	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	MBR, T	H_2 ppm
Bottom	0.020	A-6576	1	L	146.1	134.8	13.0	6.3	140
		(S-3795)		T	142.2	131.3	15.0	4.0	-
			2	L	148.9	135.5	16.0	4.8	120
				T	141.5	128.6	11.0	5.0	-
			3	L	145.9	133.8	15.5	3.8	140
				T	138.8	128.6	17.0	4.8	-
			4	L	147.3	135.1	21.0	3.2	140
				T	138.5	128.3	15.5	4.0	-
			5	L	141.7	129.8	15.5	3.8	130
				T	139.9	129.6	13.5	3.2	-
			6	L	143.3	132.3	11.0	3.2	140
				T	140.9	131.0	16.5	4.0	-
Top	0.062	A-6574	1	L	138.1	125.7	13.5	2.4	70
		(S-3793)		T	137.1	125.8	15.5	3.1	-
			2	L	137.0	124.6	16.5	2.4	70
				T	-	-	-	-	-
			3	L	138.4	126.4	15.0	2.4	80
				T	137.5	125.5	15.0	3.2	-
			4	L	138.2	125.0	17.0	2.4	90
				T	136.1	124.1	15.0	3.1	-
			5	L	138.3	128.6	15.0	3.1	70
				T	132.5	128.1	17.0	3.2	-
Bottom	0.090	A-6750	1	L	13[illegible].6	124.1	19.0	3.3	60
		(S-3791)		T	137.6	126.7	15.5	3.1	-
			3	L	137.9	128.6	15.5	3.3	60
				T	136.1	127.6	15.0	3.1	-
			4	L	138.2	127.9	15.5	3.3	70
				T	136.2	126.0	16.0	3.3	-

measured several inches from the end of one of these sheets after mill annealing and rough grinding. Thus, with better flatness after final annealing, which is now being achieved, the ductility levels should be higher and the hydrogen content lowered, since much more thorough finishing operations can be effected. However, even with these improvments, the hydrogen level will be followed closely in future processing of thin-gage sheets of Ti-7Al-12Zr to determine whether procedural changes are required to keep the hydrogen at low levels.

On the basis of the data from these 26 sheets, the following property specifications seem reasonable and were recommended to the Navy Bureau of Weapons:

	UTS Ksi	Y.S. (0.2%) Ksi	Elong (2in) %	Min.Bend Radius,T	H_2 ppm
Ti-5Al-5Sn-5Zr	120 min	110 min	12 min	4.0 max	150 max
Ti-7Al-12Zr	130 min	120 min	10 min	4.0 max	100 max

These release specifications were offered at a Titanium Sheet Rolling Meeting held in New York on June 13, 1961. At this meeting the proposed specification for Ti-5Al-5Sn-5Zr was accepted as listed above, except that the bendability requirement was relaxed to 4.5T for 0.070in and thinner and 5.0T for sheets thicker than 0.070in. This adjustment was made because the other producer felt that the 4.0T bend radius would be very difficult to meet.

The specification for Ti-7Al-12Zr was held in abeyance pending more data from the other two titanium producers who are processing this alloy. However, it was agreed that some control of the sheet quality should be exercised during this interim period; consequently, the following was accepted as a temporary specification for Ti-7Al-12Zr:

5.0T max. Bend Radius
10 percent min. Elongation
0.12 percent max. Oxygen
100 ppm max. Hydrogen

At this meeting the Navy Bureau of Weapons also requested that 25 percent of all Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheets in the production phase of the contract be tensile tested at 800F. It was agreed that such testing would be performed, since the alloys being produced in the contract were designed for superior elevated-temperature properties. However, because

Contract NOas 59-6227-c is nearing completion, it was realized that these 800F data can be used only for design allowables or capability requirements and not to establish an automatic release property specification for sheets on this contract.

In the production phase of the contract, processing of sheets from the three 1700-pound ingots of each alloy (a total of six heats) was continued with the balance of the vacuum annealed intermediate-size sheet bars being finish rolled from 1750F. Substantial improvements were made in minimizing the incidence of surface defects in hot rolled sheets, a problem described in the Eleventh Bimonthly Report(3), but even so a few more sheets were scrapped because of transverse ripples. Several sheets were mill annealed at 1350F (8 hrs), rough ground, final annealed at 1650F (1/2 hr) AC, finish ground, pickled, and are being tested (including tensile testing of 25 percent of the sheets at 800F). However, available properties are quite limited and, therefore, tabulation of data will be deferred until the Summary Report. It was observed, however, that properties are being obtained which are quite comparable to those listed in Tables 28 and 29.

As indicated in the Eleventh Bimonthly Report(3), one additional 1700-pound ingot of each of the two alloys was melted because of the shortage of slab stock and finished sheets of each composition. Thest two ingots (V-1913 and V-1914) were satisfactorily pressed to 2 7/8 x 12in slabs from 2050F (with reheating at 1950F), conditioned, and 1in thick slices were cut from the original top, middle, and bottom locations of each heat for chemical analyses. Results of these analyses are listed in Table 30 and show that both ingots are of the correct composition with good uniformity of alloy additions.

Following chemical analyses, sheet bars were scheduled to produce 21 sheets of Ti-5Al-5Sn-5Zr from V-1913 and 27 sheets of Ti-7Al-12Zr from V-1914. However, after the sheet bars were cut, internal defects were observed in that portion of V-1914M corresponding to three pieces of 0.040in Ti-7Al-12Zr and these sheet bars were discarded. Therefore, a total of 45 sheets were scheduled for rolling from the two heats as follows:

Heat and Ingot Location	Gage, in	No. of Sheets (36 x 96in)
Ti-5Al-5Sn-5Zr		
V-1913B	0.020	3
V-1913M	0.040	6

(Continued)

TABLE 30. CHEMICAL ANALYSES OF ONE 1700-POUND INGOT EACH OF Ti-5Al-5Sn-5Zr AND Ti-7Al-12Zr (Samples taken from 1-in slices of conditioned 2 7/8 x 12in pressed slabs)

Heat No. and Position	Chemical Analyses, %						
	Al	Sn	Zr	Fe	C	N_2	O_2
Ti-5Al-5Sn-5Zr							
V-1913 Top	4.96	5.00	5.04	0.057	0.022	0.011	0.077
Middle	4.87	4.99	5.05	0.063	0.016	0.010	0.066
Bottom	4.89	5.01	4.99	0.035	0.024	0.009	0.071
V-1913 Average	4.91	5.00	5.03	0.052	0.021	0.010	0.071
Ti-7Al-12Zr							
V-1914 Top	6.96	-	11.96	0.074	0.020	0.010	0.073
Middle	6.90	-	11.59	0.067	0.016	0.024	0.076
Bottom	6.93	-	11.73	0.058	0.024	0.015	0.087
V-1914 Average	6.93	-	11.76	0.066	0.020	0.016	0.079

Heat and Ingot Location	Gage, in	No. of Sheets (36 x 96in)
Ti-5Al-5Sn-5Zr	(Cont'd)	
V-1913M	0.062	4
V-1913T	0.090	5
V-1913B	0.125	3
		21
Ti-7Al-12Zr		
V-1914T	0.020	12
V-1914M	0.040	3
V-1914M	0.062	4
V-1914B	0.125	5
		24

The sheet bars were rolled to an intermediate stage from 1880-1900F without encountering the edge and surface cracking difficulties that had been so prominent in several bars from the first six ingots. The fact that the material rolled with no real problem is attributed to the improved conditioning of the pressed slabs. After intermediate rolling, the sheet bars were descaled, pickled, conditioned, and vacuum annealed at 1350F. Finish rolling of this material from 1750F will be performed early in July with all finishing operations scheduled for completion on both alloys by August 31, 1961.

A general status of the production of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheets in the contract is summarized below:

Status of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr Sheets

	Number of Sheets*			Navy-Approved Customer Orders	
Gage, in	Ordered	In Process	Completed	Ordered	Shipped
Ti-5Al-5Sn-5Zr					
0.020	18	23	6	3 1/2	0
0.040	14	22	8	3 1/2	0
0.062	12	14	0	3 1/2	0

(Continued)

	Number of Sheets*			Navy-Approved Customer Orders	
Gage, in	Ordered	In Process	Completed	Ordered	Shipped
Ti-5Al-5Sn-5Zr (Cont'd)					
0.090	10	15	6	3 1/2	0
0.125	8	11	6	2 1/2	0
Total	62	85	26	16 1/2	0
Ti-7Al-12Zr					
0.020	18	21	0	2 1/2	0
0.040	14	16	0	2 1/2	0
0.062	12	16	0	2 1/2	0
0.090	10	13	2	3 1/2	0
0.125	8	8	0	2 1/2	0
Total	62	74	2	13 1/2	0

* Equivalent of 36 x 96in sheets

As indicated above, it is estimated that all processing of these sheets will be completed by August 31, 1961, and that material for the existing individual customer orders will, for the most part, also be shipped or ready to ship by that date.

FUTURE WORK

Ti-8Al-1Mo-1V

Item 1

Practically all of the laboratory studies have been completed on Ti-8Al-1Mo-1V sheet; the only outstanding investigation is the one to determine the effect of 1100 and 1300F stress relieving cycles on the welded properties. This study will be completed, along with any other short range programs, during July and August, 1961, and results will be presented in the Summary Report.

Item 2

Processing of all Ti-8Al-1Mo-1V to provide 3000 pounds of mill annealed material in the production phase of the contract will be continued with completion scheduled by August 31, 1961.

Shipment of material on existing Navy-approved orders should also be substantially complete by this date. Aside from the normal room-temperature tensile and bend testing of each sheet, 25 percent of the material will be tensile tested at 800F and a complete listing of all such properties will be included in the Summary Report.

Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr

Item 1

The major laboratory investigations have been completed on both alloys except for determining the effect of 1200 and 1300F stress relieving treatments on the welded properties of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheet. Results of this study, plus any other short-term investigations which may arise, will be completed in August, 1961, and listed in the Summary Report.

Item 2

Processing of all remaining sheets of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr will be continued with an estimated completion date of August 31, 1961, for 2000 pounds of finished material from each alloy. Shipment of material on existing Navy-approved orders should also be substantially complete by this date. Each sheet will be tensile and bend tested at room temperature with 25 percent of all material being tensile tested at 800F, and a complete listing of all such properties for both alloys will be included in the Summary Report.

REFERENCES

1) Eighth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr, Navy Bureau of Weapons' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 30 June 1961.

2) Ninth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr, Navy Bureau of Weapons' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 7 July 1961.

3) Eleventh Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr, Navy Bureau of Weapons' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 31 August 1961.

4) Fourth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Navy Bureau of Aeronautics Contract NOas 59-6227-c, Titanium Metals Corporation of America, 29 February 1960.

5) Fifth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Navy Bureau of Aeronautics Contract NOas 59-6227-c, Titanium Metals Corporation of America, 17 October 1960.

6) Sixth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr, Navy Bureau of Weapons' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 30 March 1961.

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